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CFD EXPLOSION SENSITIVITY ANALYSIS

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EXECUTIVE SUMMARY

This paper describes the various activities involved in conducting a number of Quantitative Risk Assessments (QRA) to identify possible risk reduction measures for an offshore platform being located in an Arctic environment.

The program consisted of a number of studies, briefly described in part one, that basically surveyed different options to provide a quantitative basis for narrowing the focus to an option that could then be subjected to a sensitivity analysis.

One of the valuable characteristics of a QRA study is the ability to compare various options in a sensitivity analysis to determine the advantages/disadvantages of changes in design.

Part two of this paper then presents the actual outputs from the QRA to demonstrate the information available to the design engineers on the project.

All activities described occurred during the Front End Engineering Design (FEED) phase of the project, starting as soon as the information necessary to start the study was available.

It should be emphasized that this particular study was undertaken for an offshore platform, but the principles apply to any type of process where significant hazards are present. In fact, the author is currently involved in the extensive use of a QRA to optimize the FEED portion of an Ethylene Oxide (EO) project.

1.0 STUDY OVERVIEW

1.1 INTRODUCTION

A Quantitative Risk Analysis (QRA) study was initiated to explore various options for a platform being located in an arctic environment. Platforms located in such a harsh environment must have their processes enclosed, which creates confined spaces that in the case of a hydrocarbon Loss of Containment (LoC), can lead to devastating explosions. Unfortunately, a standard naturally ventilated module design is unlikely to be effective due to the cold working environment and potential icing.

This requires a detailed risk analysis approach to develop a design for effective and safe production. As a part of the process of obtaining a safe and effective design, an extensive series of CFD (computational fluid dynamics) simulations has been undertaken to identify the best possible design for the arctic platform. The CFD simulations were carried out by a specialist safety consulting company.

The advanced CFD studies undertaken are considered to represent a state-of-the art in technical approach to improve the knowledge of arctic challenges and identify how to establish a safe design in such an environment. It is also considered a state-of-the-art approach to verify that the accidental risk is at an acceptable low level.

A series of studies were produced for input to the design of the platform. The list of studies are:

CFD Fire and Explosion Model and Study Basis. This study contains the study basis and input data for explosion modeling. There is no direct impact on design from this report.

Sensitivity Analysis, exploring the magnitude of effect on overpressure of various parameters. This is the subject of the present report.

Drilling Areas Fire and Explosion Loads.

Helideck Turbulence and Thermals.

Manifold Area (P01) Fire and Explosion Assessment.

Well bay (W01) Fire and Explosion Assessment.

Crude Export Pump Area (P02) Fire and Explosion Loads.

Gas Compression module (P05) Fire and Explosion Loads.

Separation/Combining the Separator module (P09) and Export pump module (P02).

2.0 SENSITIVITY ANALYSIS

The subject of this paper is a series of Sensitivity Analysis studies. The purpose of which is to gain a detailed understanding of the explosion risk drivers on the platform, and identify the best possible practicable configurations of the identified risk drivers.

In order to obtain vital information as soon as possible, the CFD study was carried out in three phases:

Phase 1: The first phase of studies was carried out for a very early version of the platform design (30% review stage of geometry model) and the results were used to identify risk drivers (e.g. identifying the risk benefit from using few and large process modules versus using many smaller modules).

Phase 2: The second series of studies was used to verify the technical approach for confined modules, and identify the main risk drivers.

Phase 3: The third series of studies was used to identify the best configurations for the identified main risk drivers. For phase 3 simulations, the geometry model was updated to a 60% complete level.

It should be noted that the sensitivity studies were performed at different stages (phases) of the platform design. The numerical values calculated in the sensitivities (e.g. 1•10-4 pressure and gas cloud sizes) may therefore be different from the most recent design values. However, the conclusions of the sensitivity studies (e.g. the recommendations for safest design) are still valid.

The sensitivity studies in this series of studies should be seen as documentation on how various input parameters influence the explosion risk.

3.0 STUDIES

3.1 MOVING GAS LIFT MANIFOLD AWAY FROM WELLBAY RELIEF WALLS

By moving the gas lift manifold away from the relief walls, the sensitivity study shows that the explosion pressure generated inside the W01 Wellbay area is only moderately sensitive to the distance the gas lift manifold is located away from the eastern wall.

The variation of explosion load is less than 2% for all tested locations of the manifold. The difference is not significant in terms of establishing an explosion design basis.

3.2 BLOWDOWN DELAY TIME

The explosion pressure Design Accident Load (DAL) is only moderately sensitive to the blowdown delay in the P01 Manifold area.

By reducing the blowdown delay with 50% the $1 \cdot 10^{-4}$ load is calculated to be 1.396 barg (representing a decrease of 1.4%).

By increasing the blowdown delay with 100% the $1 \cdot 10^{-4}$ load is calculated to 1.433 barg (representing an increase of 1.2%).

Were blowdown to be delayed significantly beyond 2 minutes then this sensitivity would need to be re-assessed. This sensitivity analysis was run for the P01 Manifolds area but the overall conclusion that explosion design overpressure is not sensitive to changes in blowdown time between 1minute and 4 minutes is applicable to all explosion areas.

3.3 AMOUNT OF HOT WORK

The explosion pressure DAL is not very sensitive to the amount of hot work in the P01 manifold area.

By reducing the amount of hot work 50%, the $1 \cdot 10^{-4}$ load is calculated to still be 1.601 barg (representing a decrease of 0.3 %).

By increasing the amount of hot work 100%, the $1 \cdot 10^{-4}$ load is calculated to still be 1.615 barg (representing an increase of 0.6 %).

This sensitivity analysis was run for the P01 Manifolds area but the overall conclusion that explosion design overpressure is not sensitive to variations in the assumed value of hot work between 25 and 100 hours per year is applicable to all explosion areas.

3.4 GAS DETECTOR DETECTION

The complete gas detector density screening study was the subject of another study. The summary of findings and recommendations for that study are below.

A gas detector density screening study was performed for the P01 Manifold and P05 Gas Compressor modules using probabilistic explosion analysis tool ExploRAM. The following has been concluded from the study:

The requirement in Fire and Gas Detector Layout of 5 meter maximum detector spacing is confirmed to be a reasonable requirement also for the confined platform modules.

By increasing the gas detector grid distance from 5x5 m to 6x6 m in the P01 Manifold module, the 8·10-5 load (the recommended design accidental load) increases by 5.6 % (from 0.39 barg to 0.42 barg). Reducing the detector distance to 4x4 meters only reduces the 8·10-5 load by 1.8%.

By increasing the gas detector grid distance from 5x5 m to 6x6 m in the P05 Gas Compressor module, the 8·10-5 load (the recommended design accidental load) increases by 1.6 %. Reducing the detector distance to 4x4 meters only reduces the 8·10-5 load by 0.3%.

A similar effect (detector spacing of 5 meter) is seen in the resulting fire frequencies, both in P01 and P05. Increasing the detector spacing has a more significant effect than decreasing the spacing.

Based on the findings of this study, the recommendation is a maximum 5 meter detector spacing.

3.5 RELIEF PANEL DESIGN PARAMETERS

Three sensitivities, listed below, were run independently of each other, all for the P01 Manifolds area:

Relief Area: Decreasing the relief area by approximately 50 % in the P01 manifold area results in an increase of explosion pressure from 1.6 barg (base case) to 2.0 barg. The design explosion load for the P01 Manifolds area increased by 25%.

Relief panel weight: Increasing the relief panel weight by approximately 50 % in the P01 manifold area results in an increase of explosion pressure from 1.6 barg (base case) to 2.2 barg. The design explosion load for the P01 Manifolds area increased by 36%.

Panel relief pressure: Increasing the relief panel opening pressure by a factor of 4 from 0.05 barg to 0.2 barg in the P01 manifold area results in an increase of the explosion pressure from 1.6 barg (base case) to 2.0 barg. The design explosion load for the P01 Manifolds area increased by 25%.

The results show that relief panel parameters have a significant effect on explosion overpressures for the explosion case assessed. However, these results cannot be extrapolated to other explosion cases and the sensitivity of explosion results to variations in relief panel parameters will need to be considered for each explosion area.

3.6 LEAK FREQUENCY

The explosion pressure DAL is significantly dependent on the leak frequency input. The potential for changes in leak frequencies as the design develops will need to be considered when establishing the design basis overpressure for each area.

By reducing the leak frequency 50 %, the $1 \cdot 10^{-4}$ load is calculated to 1.1 barg (representing a decrease of 34%).

By increasing the leak frequency 100 %, the $1 \cdot 10^{-4}$ load is calculated to 2.5 barg (representing an increase of 56%).

The explosion pressure DAL is moderately dependent on the leak frequency input. The gas lift manifold contributes to approximately 31% of the total leak frequency used in the base case analysis.

By moving the gas lift manifold out of the Wellbay area, the $1 \cdot 10^{-4}$ load is calculated to be 0.34 barg (representing a decrease of 8.9%).

The reason why the 10-4 load is reduced with only 8.9% when the frequency is reduced with 31% is twofold; first of all, the segment volume of the gas manifold is small compared to the volumes involved with well flow leaks. Secondly, the shape of the pressure frequency curve causes the relation between frequency change and pressure change to be a non-one to one relation.

3.7 CUT-OFF HYDROCARBON RELEASE RATE

The explosion pressure DAL load is not sensitive to a lower cut-off rate. It was previously determined that medium leaks are the dominant for the explosion load.

This is as expected, since leaks below 0.05 kg/s will not be able to form flammable gas clouds large enough to produce explosion loads if ignited.

3.8 NUMBER OF PUMPS

The explosion pressure DAL is not sensitive to the number of pumps in the P01 manifold area (note that if the number of pumps increases significantly from the simulated, the results for the DAL dependency may increase).

By reducing the number of number of pumps 50%, the $1 \cdot 10^{-4}$ load is calculated to still be 1.606 barg (representing a decrease of 0.002%).

By increasing the number of pumps 100%, the $1 \cdot 10^{-4}$ load is calculated to still be 1.606 barg (representing an increase of 0.004%).

3.9 DELUGE SYSTEMS

The use of deluge systems in the P01 manifold area demonstrated a positive effect in decreasing the explosion pressure. Large droplet sizes show the best effect to reduce the explosion pressure. According to the Norwegian PSA (the Facilities Regulations §36) automatic release of deluge is required if it can reduce the explosion risk.

The presence of water droplets (e.g. from deluge or water based explosion mitigation systems) at the time of explosion reduced design basis overpressures by: 11% (200µm droplet size), 26% (600µm droplet size), 38% (1800µm droplet size). However, passive means of mitigating the effects of explosion overpressure, primarily by the design of barriers to withstand credible explosion loads (i.e. prevent escalation into adjacent areas) are preferred.

3.10 IGNITION SOURCE ISOLATION EFFICIENCY

The efficiency of the ignition source isolation upon ESD is critical in confined modules. The efficiency of isolation of ignition sources on this platform has therefore been assessed in more detail than what is normally undertaken in explosion simulations on open (naturally ventilated) modules.

The activity level for personnel activities upon ESD is assessed to be 1% of the normal activity level in any module. This is consistent with the conclusions from the new Norwegian OLF ignition model.

The isolation efficiency of electrical equipment is preliminarily assessed to be 85% (i.e. 15% of all electrical equipment remains active also after ESD). This is according to best practice in the North Sea for platforms with modern design of electrical equipment (and their safety actions). This performance used in this study presumes that the electrical design is moderately better than the average platform in the North Sea (including older platforms).

The efficiency of isolation of electrical equipment will be evaluated in more detail for each module during detail design. Until results from the detailed evaluation are available, the efficiency of 15% (remaining ignition intensities after ESD) will be used as the base case for all modules.

Clearly the likelihood of ignition of flammable gas clouds can have a significant effect on explosion risk and therefore design overpressure. On an area by area basis the efficiency of electrical isolation will reviewed during detail design. The results of these reviews will be factored into the setting of explosion design overpressures.

The explosion pressure DAL is very sensitive to the isolation efficiency in the P01 manifold area.

By reducing the isolation efficiency 50%, the $1 \cdot 10^{-4}$ load is calculated to be 1.71 barg (representing an increase of 21%).

By increasing the isolation efficiency 100%, the $1 \cdot 10^{-4}$ load is calculated to be 1.12 barg (representing a decrease of 21%).

NOTE: The simulations in this series of studies was carried out as an early indication of the explosion risk drivers in the enclosed modules. All simulations were carried out using the standard cloud model of ExploRAM. In the modified version of ExploRAM (which is now recommended to be used in all confined modules) it is seen that the isolation efficiency is even more important than described in this paper.

The effects of variations in electrical isolation efficiency on ignition probability and design basis overpressure are quantified. As stated above, clearly the likelihood of ignition of flammable gas clouds can have a significant effect on explosion risk and therefore design overpressure. On an area by area basis the efficiency of electrical isolation must reviewed during detail design. The results of these reviews will be factored into the setting of explosion design overpressures.

4.0 COMBINING SEPARATOR (P09) AND EXPORT PUMP (P02) MODULES

4.1 EXPLOSION RISK ANALYSIS - EXPLOSION LOADS

The pressure-frequency curves for combining the Separator module (P09) and the Export Pump module (P02) on the platform have been calculated in a detailed explosion analysis according to NORSOK Z-013, Annex G.

The explosion loads in P09 will increase by approximately 79% if the module is combined with P02 (from 0.19 barg to 0.34 barg for the 8E-5 load). The frequency for exceeding 0.3 barg increases from 6.8E-5 for P09 alone to 8.4E-5 when P02 and P09 are combined (an increase of approximately 24%).

The increase in explosion loads in P02 will be even higher than the increase seen in P09 if the two modules are combined. The frequency for exceeding 0.3 barg increases from 7.0E-6 for P02 alone to 8.4E-5 when P02 and P09 are combined (an increase of approximately 1100%).

The total leak frequency for gaseous leaks above 0.05 kg/s for the combined module is 4.27E-2 per year. This corresponds to one leak approximately every 23 years. The corresponding leak frequencies for P02 and P09 as standalone modules are 1.01E-2 and 3.25E-2, respectively.

The calculated fire frequency for the combined module is calculated to 1.89E-4 per year. This corresponds to one fire approximately every 5300 years.

The explosion loads with return frequency between 10^{-4} and 10^{-5} are presented in Table 1. The corresponding pressure-frequency curves are also presented below. The corresponding durations are calculated to:

50 - 450 ms for loads below 0.5 barg
50 - 300 ms for loads between 0.5 and 1.5 barg

50 - 200 ms for loads above 1.5 barg.

Table 1: Calculated load with frequency between 10-4 and 10-5

	P02 Export Pump			P09 Separator			Combined P02 + P09		
	1.0E-04	8.0E-05	1.0E-05	1.0E-04	8.0E-05	1.0E-05	1.0E-04	8.0E-05	1.0E-05
LOCAL PRESSURE	N/A	N/A	0.13	0.10	0.19	6.13	0.18	0.34	4.72
GLOBAL PRESSURE	N/A	N/A	0.09	0.08	0.15	4.89	0.11	0.22	2.99
DRAG	N/A	N/A	0.01	0.02	0.03	1.02	0.02	0.05	0.66
ADJACENT PRESSURE	N/A	N/A	0.03	0.02	0.04	1.19	0.04	0.09	1.20
OUTSIDE DRAG 1M	N/A	N/A	0.02	0.02	0.04	1.17	0.04	0.07	0.96
OUTSIDE DRAG 5M	N/A	N/A	0.01	0.01	0.03	0.94	0.02	0.04	0.55

The main reason for the low 10^{-4} explosion loads is the low leak frequencies and the effective isolation of ignition sources after ESD.

Since the minimum design load is 0.3 barg, the changes in the design loads for P02 and P09 are not significant if combining them into one larger module. However, the total impairment frequency will increase (but still remain below the acceptance criterion). The total frequency for exceeding 0.3 barg increases from 7.5E-5 when the modules are separated (7.0E-6 for P02 and 6.8E-5 for P09) to 8.4E-5 when the two modules are combined.

Explosion risk from methanol leaks in P02 Export Pump Module was not calculated in detail in this study, and it is expected that methanol leaks may have some impact on the pressure frequency curve for P02. However, even though methanol leaks may slightly alter the numbers calculated in this study, the main conclusions presented herein are considered to be valid.

4.2 FIRE AND SMOKE - COMBINING AND SEPARATION OF MODULES

An internal fire and smoke study both with separate P02 Export Pump and the P09 Separator Module and a combined P02 and P09 has been conducted. The main objective has been to evaluate personnel safety during escape in the initial phase of a fire event. The effect of internal loss of containment (LoC), resulting in fires, in terms of impairment of personnel escape due to heat radiation, temperature and smoke, were investigated and quantified.

From the findings in this study general conclusions can be drawn, based on a more qualitative evaluation of the results. The approach has, in other words, not been to undertake a full probabilistic study, i.e. take into account leak frequencies, leak durations, leak directions or ignition probabilities. The results and conclusions from the fire and smoke part should therefore be seen in connection with the above mentioned factors.

4.2.1 P02 and P09 Separated

Up to 20-30 % of the module would be impaired more or less instantly by radiation, in case of a 1 kg/s fire in P02 or P09. Fires located low in the module tend to impair a larger area, compared with fires located higher up in the module.

With the exception of radiation, visibility is seen to be the first criterion to be impaired.

Personnel located at the upper deck will have very little time before soot and other combustion products will obstruct the visibility (<5m). The temperature on the upper deck will also rise quickly. *The time to* impairment *of escape on the upper deck is <10-20s for >0.5kg/s ignited leaks.*

Personnel on the lower deck will have slightly more time to escape than personnel on the upper deck. *The time to impairment of escape on the lower deck is <30-35s for >0.5kg/s ignited leaks.*

4.2.2 P02 and P09 combined

Up to 20-25 % of the combined module would be impaired more or less instantly by radiation, in case of a <2 kg/s fire. Fires located low in the module tend to impair a larger area, compared with fires located higher up in the module.

With the exception of radiation, visibility is seen to be the first criterion to be impaired.

The combination of P02 and P09 into one fire zone, result in a slim and tall module that span over 4 decks. From simulations in P05 Gas Compression Area, which is a similar shaped module, The build-up of the smoke layer from the ceiling to the deck, slows down once it reaches the elevation of the fire.

This observation would also be applicable for fires in a combined P02 and P09. For example a 0.5 kg/s fire on Production Deck would quickly (less than 30s) impair escape on the Production and Upper Mezzanine Deck, while personnel on the decks below would have somewhat more time to escape. However, if the fire is located at the lowest deck (Cellar Deck), all decks, including the Cellar Deck, were seen to be impaired within 1 minute for a 1 kg/s fire. Therefore, the conclusion is that *a >1 kg/s fire could impair the entire module (P02 and P09 combined) within 1 minute.*

4.2.3 Combined vs. Separated P02 and P09

By combining the two areas, simulations have shown a marginal difference in the time to impairment of escape due to reduced visibility and high temperatures.

In multiple-level modules, escape from the upper elevations is impaired rapidly (15-25s), regardless of leak location, leak size and module height.

The leak frequency is 3 times higher in P02 compared to in P09.

Personnel in P09 will by removing the deck have 4 times the increased risk of being exposed to a fire since fires originating both from P02 and P09 will expose them.

Personnel in P02 will by removing the deck also have a slight increased risk of being exposed to a fire, but not to the same degree as personnel in P09. This is because only a fraction of the fires originating from P09 will affect personnel in P02.

Personnel in P02 will by removing the deck have a slight improvement in the time available for escape.

Personnel in P09 will not see an improvement in the time available for escape when the two modules are combined.

Overall recommendation, viewed from a personnel fire safety view is to keep the two modules separate, i.e. keep the wall between P02 and P09 plated.

5.0 HVAC EXPLOSION RISK DISCUSSION

The effect on the explosion risk from changing the HVAC configuration from being shut down upon gas detection and automatically re-started after 10 minutes with 12 air changes per hour (referred to as the Phase 2 Base Case) to continuously running HVAC upon gas detection and ramp it up to 20 air changes per hour (referred to as the Phase 3 Base Case) has been studied. The following is concluded from this study:

The HVAC system is seen to have a significant effect on the explosion risk.

The explosion loads in P01 Manifold module has decreased significantly by changing the HVAC philosophy. The $8 \cdot 10^{-5}$ load has been reduced from 1.21 barg (Base Case Phase 2) to 0.4 barg (Base Case Phase 3), a reduction of 67%.

The explosion loads in P05 Gas Compression module has decreased significantly by changing the HVAC philosophy. The $8 \cdot 10^{-5}$ load has been reduced from 0.69 barg (Base Case Phase 2) to 0.18 barg (Base Case Phase 3), a reduction of 74%.

The most important factors for obtaining an effective HVAC design (in terms of explosion risk) are the air changes rate and the continuity. It is favorable to use as high as possible rate (air changes per hour) and to keep HVAC running continuously also after gas detection.

The main effect from ramping up the air changes rate is that the small gas leaks become more diluted resulting in smaller flammable gas clouds. Even though large leaks also become more diluted, resulting in larger flammable gas clouds, the positive effects on small leaks are more significant than the negative effects on large leaks (frequency for small leaks is higher than large leaks). In addition, flammable gas is in general vented out more quickly when the air changes per hour (ACH) increases. As a result, the total effect from increasing the ACH rate is positive.

The main effect from continuous HVAC is that the flammable gas is more quickly vented out of the module than if the HVAC is shut down and restarted after 10 minutes. In addition, small (and high frequent) leaks give much smaller flammable volumes when the HVAC is running.

The effects of the other factors varied in this study (pull/push, unbalance and seepage) are small compared to the above factors. Seepage is in this context defined as unintended leakage through small holes and cracks due to fabrication imperfections and subsequent modification work throughout a facility's life.

The seepage does have a moderate effect on the explosion risk. Changing seepage area and locations had an opposite effects in P01 and P05 (increasing loads with 28% in P01 and decreasing loads with 12% in P05). No general trend can therefore be concluded. Seepage areas cannot be used as a safety increasing measures since the exact location and total areas of seepage in the module cannot be known in advance (and is not designed, but comes as a result of imperfection in the construction).

The effect on seepage is expected to be dependent on the HVAC design (may be different from pull and push configurations, and may be different from different locations of the HVAC inlet and outlet ducting).

Changing HVAC configuration from push to pull had an opposite effects in P01 and P05 (increasing loads in P01 and decreasing loads in P05). No general trend can therefore be concluded.

Reducing the unbalance from 25% more air in than out of the module to 10% more air in than out of the module had a positive effect in both P01 and P05. Reducing the unbalance may therefore be slightly favorable, but nevertheless it may not be regarded as a safety increasing measure since the unbalance will come as a result of the target operating pressure in the module.

Changing HVAC configuration between pull and push had opposite effects in P01 and P05 (increasing loads in P01 and decreasing loads in P05). No general trend can therefore be concluded. Based on the present study it can therefore be made no general recommendation as whether to prefer pull or push (provided the given location of all ducting).

6.0 CONCLUSIONS

The results of sensitivity analysis should be taken into account when setting design overpressures for each explosion area and in the design of explosion relief panels.

It should be noted that several of the sensitivity studies were performed at an early stage of the platform design. The numerical values calculated in the sensitivities (e.g. $1\cdot10^{-4}$ pressure and gas cloud sizes) may therefore be different from the current design values. However, the conclusions of the sensitivity studies (e.g. the recommendations for safest design) are still assessed to be valid. The sensitivity studies in this paper should therefore be seen as documentation on how various input parameters influence the explosion risk.

Sensitivity analyses reported here are based on an earlier set of explosion results. Since then, design basis overpressures have reduced significantly due largely to revised Loss of Containment frequencies. This has been taken into account when drawing conclusions from the sensitivity analysis results reported here.

The HVAC optimization study recommends changing the HVAC configuration from being shut down upon gas detection and automatically re-started after 10 minutes with 12 air changes per hour to continuously run HVAC upon gas detection and ramp it up to 20 air changes per hour in terms of the explosion risk. The explosion loads in the P01 Manifold and P05 Gas Compressor modules have decreased significantly by changing the HVAC philosophy.

Overpressures are sensitive to explosion relief panel parameters i.e. relief area; overpressure at which relief panels open; panel weight (e.g. ice accumulation can increase panel weight). The effect of variations in these parameters has been established for one particular explosion case but the results cannot be extrapolated for other cases.

The results show that relief panel parameters can have a significant effect on explosion overpressures and the sensitivity of explosion results to variations in relief panel parameters will need to be considered for each explosion area.

The frequency of release of flammable gas and volatile liquids will have a significant effect on the frequency of explosions. The potential for changes in leak frequencies as the design develops will need to be considered when establishing the design basis overpressure for each area.

The presence of water droplets (e.g. from deluge or water based explosion mitigation systems) at the time of explosion reduced design basis overpressures by: 11% (200µm droplet size), 26% (600µm droplet size), 38% (1800µm droplet size). However, passive means of mitigating the effects of explosion overpressure, primarily by the design of barriers to withstand credible explosion loads (i.e. prevent escalation into adjacent areas) are preferred.

The likelihood of ignition of flammable gas clouds can have a significant effect on explosion risk and therefore design overpressure. On an area by area basis the efficiency of electrical isolation must be reviewed during detail design. The results of these reviews must be factored into the setting of explosion design overpressures.

Design basis explosion overpressures are not significantly sensitive to the following

- Moving gas lift manifold away from Wellbay relief walls
- Change in blowdown delay time in the range 1-4minutes
- Effect of change in amount of hot work in the range 25 – 100 hours per year in a given area
- Number of gas detectors above 9 per explosion area
- Moving the gas lift manifold out of the Wellbay area
- Reducing the cut-off hydrocarbon release rate from 0.05 to 0.01kg/s
- Number of pumps in manifold area.

Overpressures are sensitive by combining modules; the explosion loads in P09 Separator module will increase by approximately 79% if the module is combined with P02 Export Pump module. The increase in explosion loads in P02 will be even higher than the increase seen in P09 if the two modules are combined.

7.0 RECOMMENDATIONS

Based on the findings of the series of studies, the following recommendations are proposed:

Since the minimum design load is 0.3 barg, the changes in the design loads for P02 and P09 are not significant if combining them into one larger module. However, the total impairment frequency will increase. The total frequency for exceeding 0.3 barg increases from 7.5E-5 when the modules are separated (7.0E-6 for P02 and 6.8E-5 for P09) to 8.4E-5 when the two modules are combined.

The 8.0E-5 load (representing a 20% frequency margin) is 0.34 barg. Based on this, the design load should be 0.34 barg. However, since the frequency for 0.3 barg is only slightly higher, 8.3E-5.

This is considered to also be an acceptable design load (resulting in a safety margin of 17% rather than 20%). Based on this, it is recommended to design the walls in the combined module to resist global maximum (covering the whole wall) load of no less than 0.3 barg and a local maximum (covering 2x2 meters) load of no less than 0.3 barg (duration is 400 ms on both loads). This corresponds to an impairment frequency of approximately 8.3E-5.

The corresponding design loads for drag inside module is 0.15 barg, local load on adjacent modules is 0.2 barg, and drag load outside module is 0.15 barg. Duration is 400 ms for these loads.

The Phase 3 Base Case HVAC configuration with 20 ACH and continuous operation is seen to be the best configuration (of the simulated) for HVAC in both P01 Manifold and P05 Gas Compressor modules. The Phase 3 HVAC Base Case is seen to be significantly better than the Phase 2 HVAC Base Case (shut down upon gas detection and restarted after 10 minutes with 12 ACH) in terms of the explosion risk, and the Batch 3 Base Case is therefore recommended to be used on the modules.

The resulting design loads for P01 Manifold module should be updated based on the findings of the studies. However, when doing so, other relevant uncertainties should be considered before producing the final Phase 3 pressure-frequency curves (e.g. the relief wall configuration and the ignition source efficiency should be considered).

The resulting design loads for P05 Gas Compressor Module should be updated based on the findings of the studies However, when doing so, other relevant uncertainties should be considered before producing the final Phase 3 pressure-frequency curves (e.g. the relief wall configuration and the ignition source efficiency should be considered).

The resulting design loads for the LQ should be updated based on the findings of the studies However, when doing so, other relevant uncertainties should be considered before producing the final Phase 3 pressure-frequency curves (e.g. the relief wall configuration and the ignition source efficiency should be considered).

8.0 EXPLOSION RISK ANALYSIS MODELING RESULTS

8.1 BLAST OPTIMIZATION RESULTS FOR P01 AND P05

The FEED Phase HVAC optimization study for explosion loads in P01 Manifold and P05 Gas Compressor Modules is complete. The summary of findings and recommendations for that study is below.

The HVAC design is seen to have a significant impact on the explosion risk in confined, mechanically ventilated modules. Therefore, an explosion risk analysis according to NORSOK Z-013, Annex G has been performed for P01 Manifold and P05 Compressor modules in order to optimize the HVAC design philosophy. This study has been carried out as a part of the Phase 3 work.

The study is a continuation of the Phase 2 sensitivity studies on HVAC. Based on the Phase 2 sensitivities, the Base Case configuration for the HVAC system in Phase 3 has been changed.

This study demonstrates the effects of changing the HVAC Base Case from being shut down upon gas detection and automatically re-started after 10 minutes with 12 ACH to continuously run HVAC upon gas detection and ramp it up to 20 ACH, and the potential additional effects from further changes in the HVAC philosophy.

8.2 MAIN ASSUMPTIONS

The main assumptions for the present work are given below:

The geometry used for the P01 Manifold and P05 Compressor modules is based on March 20 2009 and the Rev. G geometry model of the platform, respectively.

The leak frequencies for P01 Manifold and P05 Compressor modules are taken from another study. If the leak frequencies are modified, the conclusions of this study will change accordingly.

The leak location used in this study is unaltered from Phase 2.

The configuration of the pressure-relief walls are taken from another of the studies. It should be noted that even though a change in the relief configuration is likely to alter the explosion load levels calculated in this study, the main conclusion on which of the tested HVAC philosophies is the best with respect to explosion risk is going to be the same for all pressure relief configurations.

The ignition source shut down philosophy is taken from another of the studies. It should be noted that even though a change in the ignition source shut down philosophy is likely to alter the explosion load levels calculated in this study, the main conclusion on which of the tested HVAC philosophies is the best with respect to explosion risk is going to be the same for all shutdown philosophies. However, it is expected that improving the shutdown efficiency (more of ignition sources are isolated upon ESD) will result in less difference between the simulated HVAC philosophies.

The ignition intensities are based on the 1996 JIP model.

The HVAC philosophies simulated in this study is described in 8.3. The base case for Phase 3 is to use 20 air changes per hour and continuous HVAC, which is different from the Phase 2 base case assuming 12 air changes per hour and shut down of HVAC upon gas detection and automatic re-start after 10 minutes. All air intake and outlet locations are unaltered from Phase 2.

A total of 18 gas leak scenarios are simulated using FLACS software. All scenarios are simulated with the same leak location, but with different transient leak rates. The transient leak rates used are taken from another of the studies.

The gas composition, temperature of the expanded gas, gas density and jet velocity used in the simulations are taken from another study.

8.3 HVAC PHILOSOPHIES

The following labeled four HVAC philosophies have been simulated for the P01 Manifold and P05 Compressor modules in order to optimize HVAC design:

20 ACH PUSH Unbalance 25 % (Base Case)
The HVAC is simulated with 20 air changes per hour with pushing effect; 25 % more air in than out of the module.

20 ACH PULL Unbalance 25 % (Sensitivity 1)
Pulling effect; 25 % more air out than in of the module.

20 ACH PUSH Unbalance 10 % (Sensitivity 2)
10 % more air in than out of the module.

20 ACH PULL Unbalance 25 % Modified Seepage (Sensitivity 3)
Different location of seepage openings and 50 % reduction in total seepage area compared to sensitivity 1. This is presented in Figure 1 and Figure 2 for the P01 Manifold module and P05 Gas Compressor module, respectively.

8.4 SEEPAGE

Since the seepage areas and location for a module cannot be identified from the design documentation, these have been randomly selected. The only technical consideration made in this respect is that the resulting air flow through the seepage (given by the unbalance of the HVAC system) shall not result in numerically challenging velocities (seepage velocities shall not be significantly larger than air intake velocity).

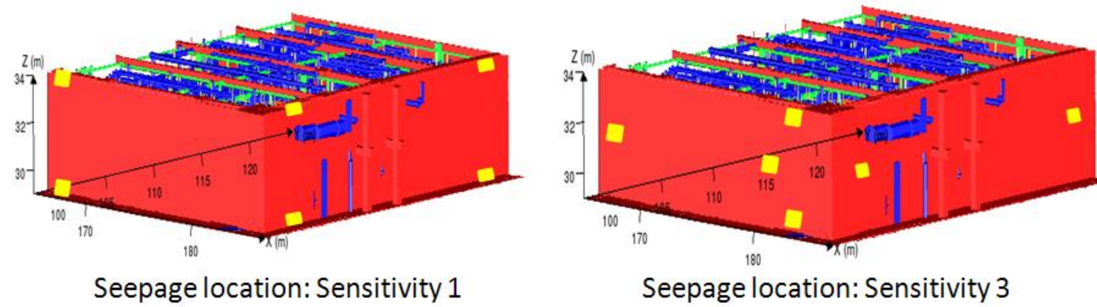

Figure 1: Seepage location (yellow plates) in sensitivity 1 and sensitivity 3 (modified seepage) for P01 Manifold module. Seepage location selected randomly

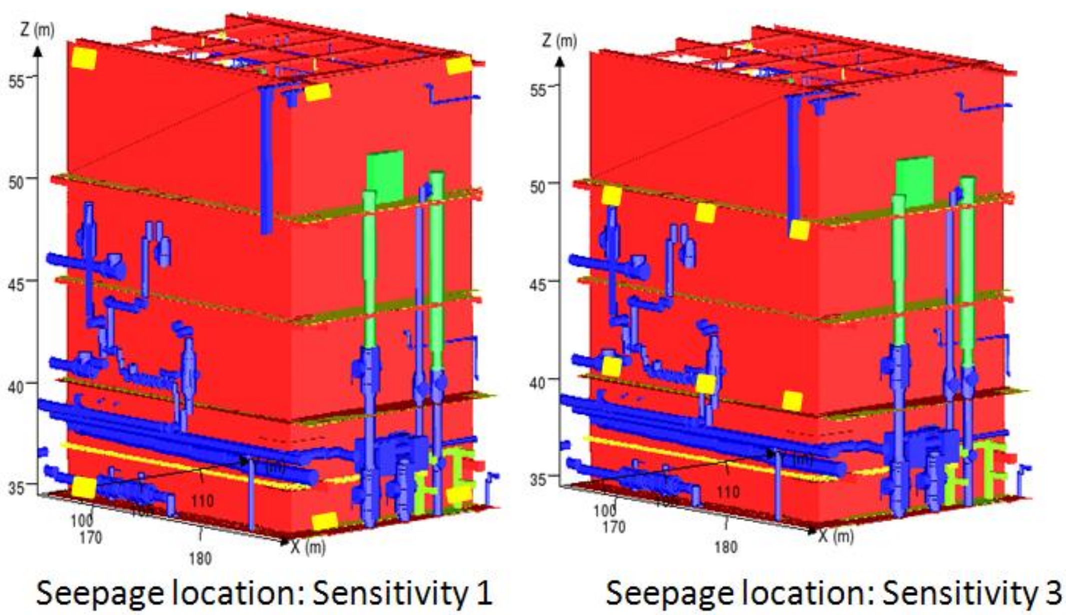

Figure 2: Seepage location (yellow plates) in sensitivity 1 and sensitivity 3 (modified seepage) for P05 Gas Compressor module. Seepage location selected randomly

8.5 DISPERSION SIMULATIONS

P01 MANIFOLD MODULE

The resulting transient flammable volumes from the FLACS simulations for the P01 Manifold Module are presented in Figure 3 through Figure 20. All FLACS scenarios are simulated in 1800 seconds (i.e. gas is traced approximately for 600-1200 seconds after the leak has stopped).

The Phase 2 results are also presented for comparison.

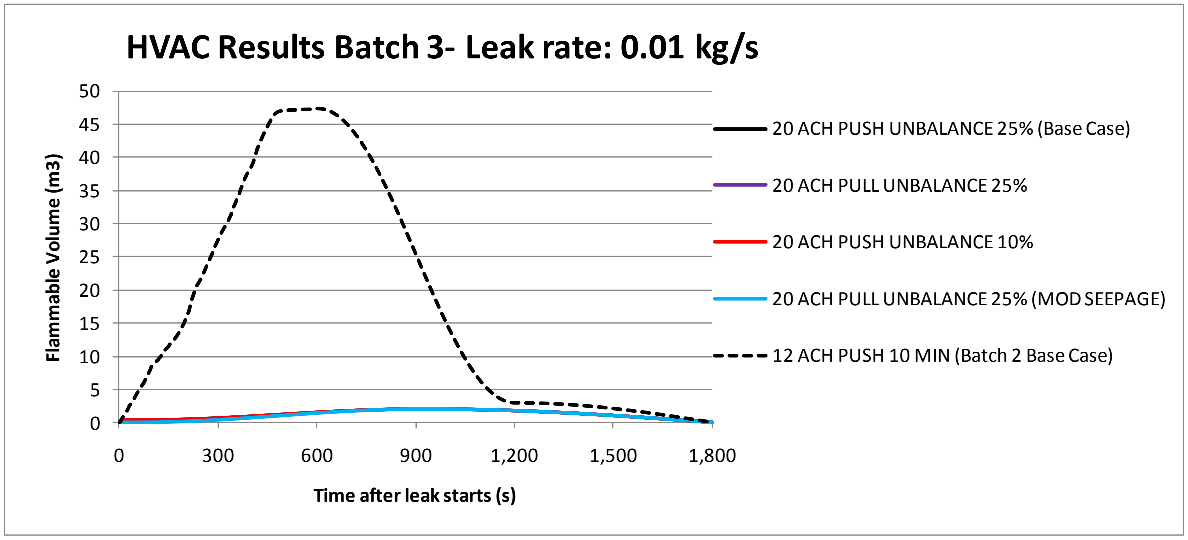

Figure 3: Transient development of flammable gas – initial leak = 0.01 kg/s

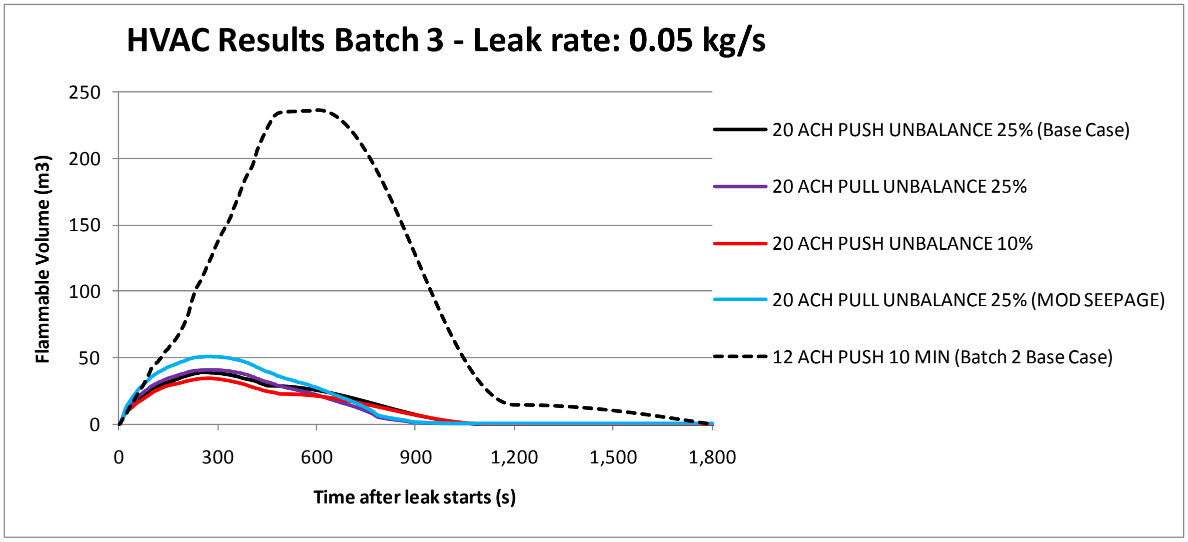

Figure 4: Transient development of flammable gas – initial leak = 0.05 kg/s

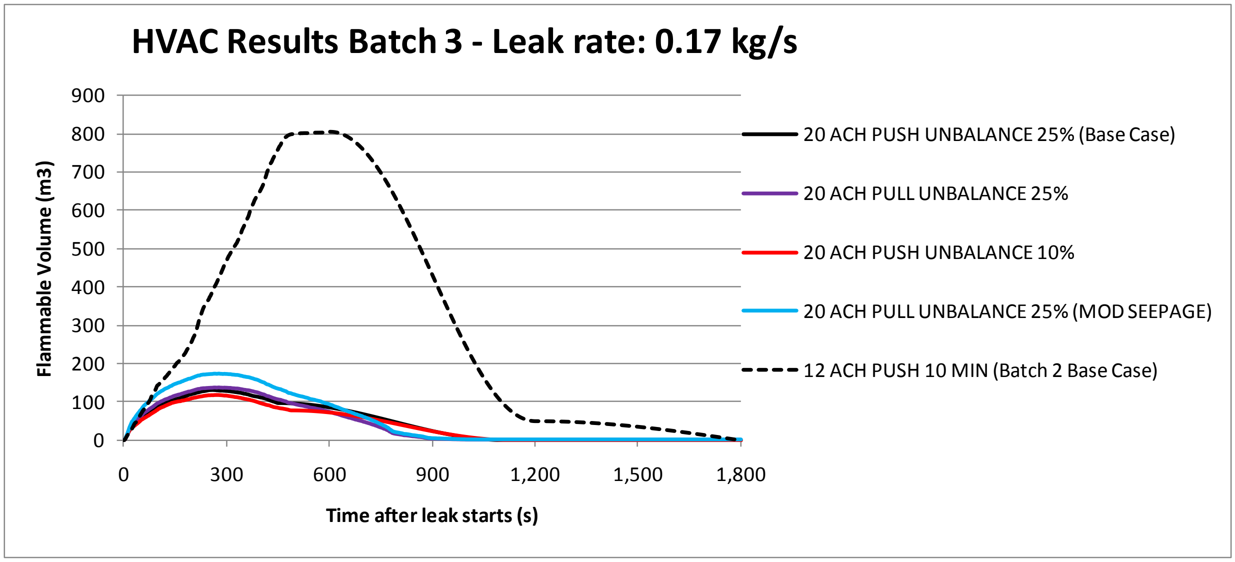

Figure 5: Transient development of flammable gas – initial leak = 0.17 kg/s

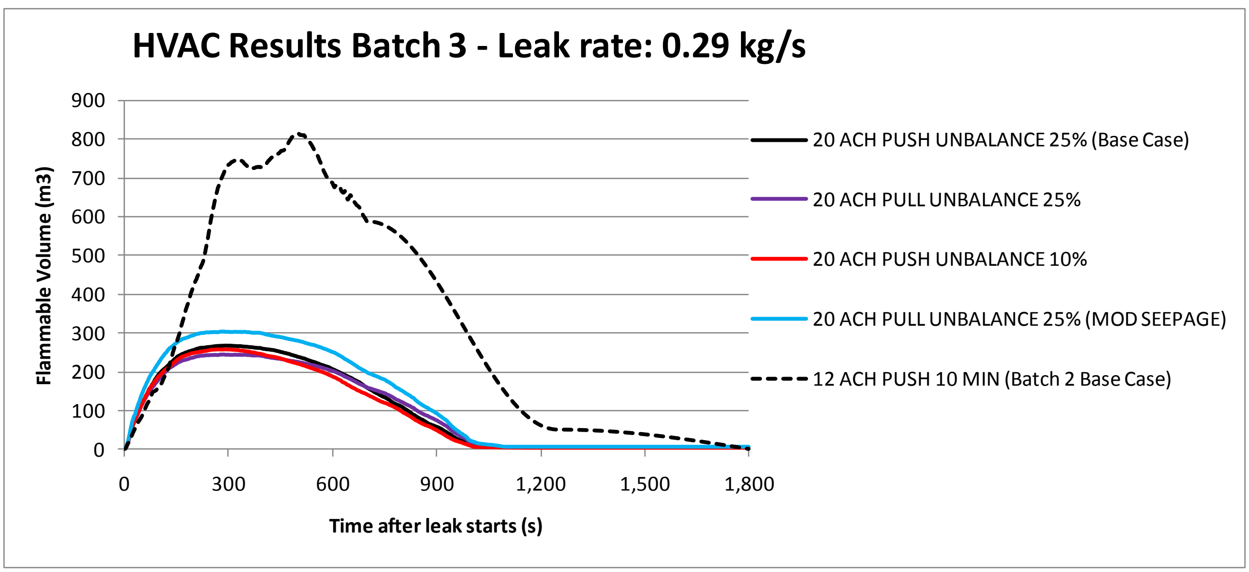

Figure 6: Transient development of flammable gas – initial leak = 0.29 kg/s

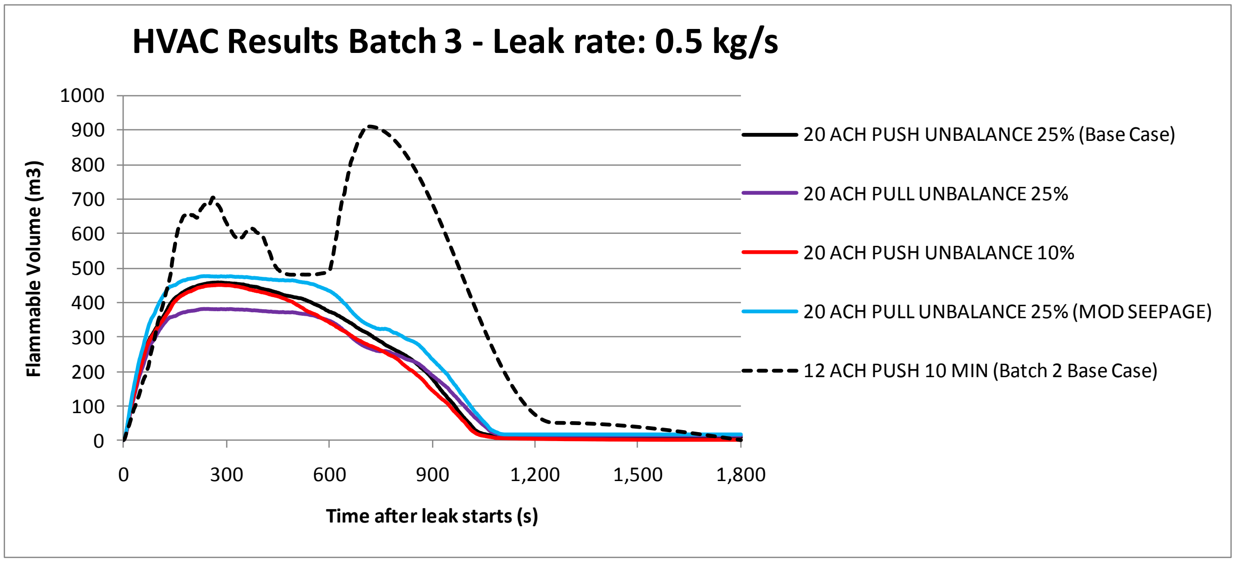

Figure 7: Transient development of flammable gas – initial leak = 0.5 kg/s

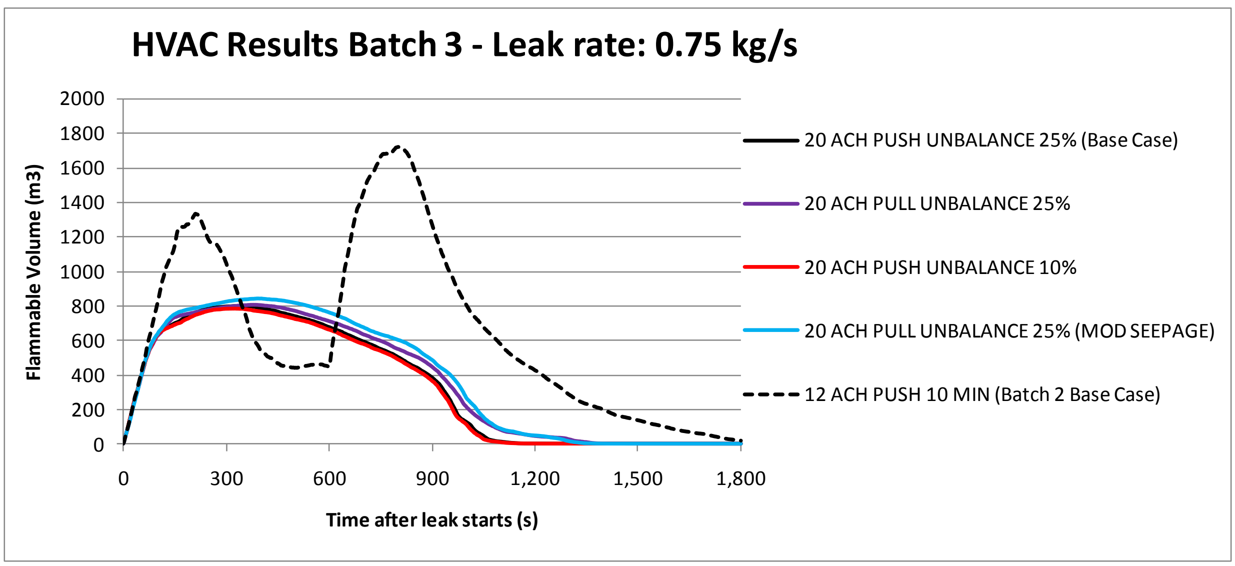

Figure 8: Transient development of flammable gas – initial leak = 0.75 kg/s

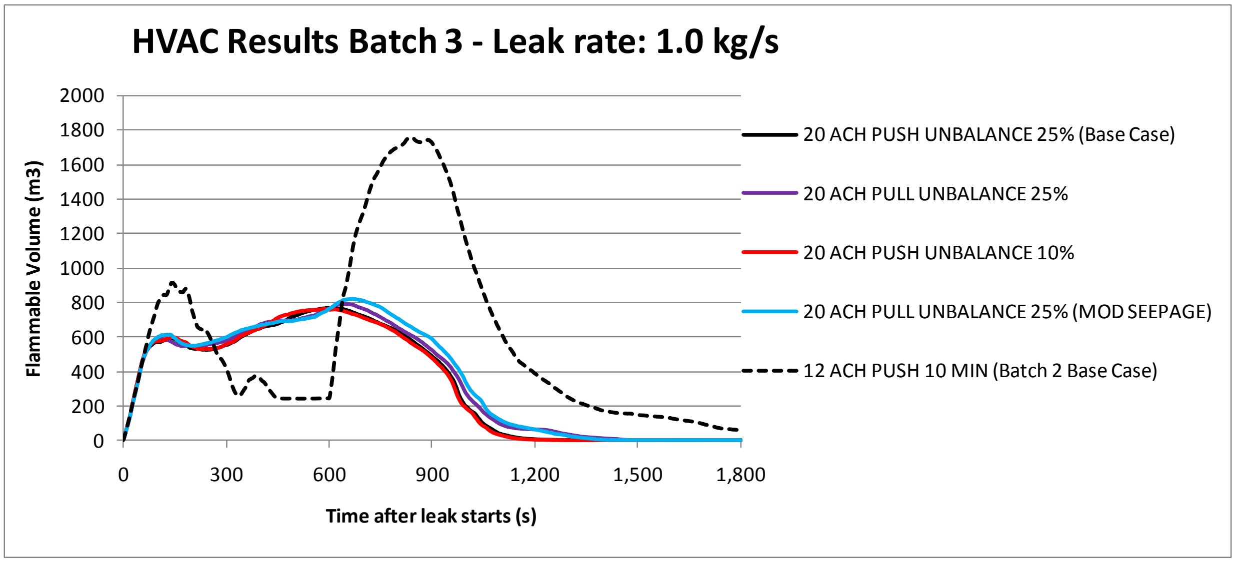

Figure 9: Transient development of flammable gas – initial leak = 1.0 kg/s

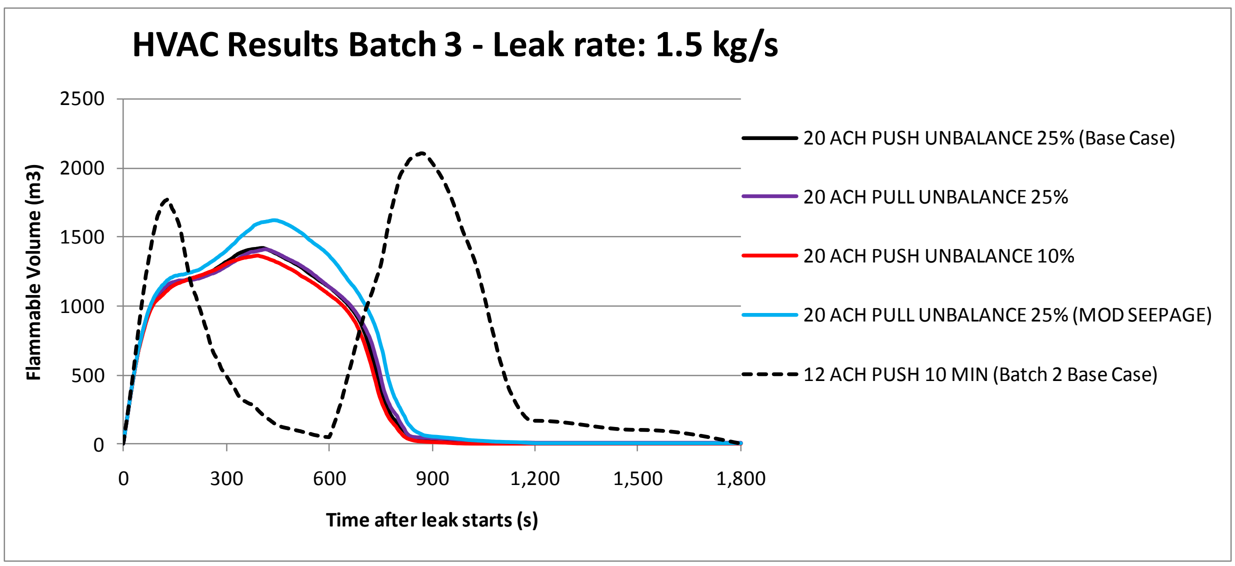

Figure 10: Transient development of flammable gas – initial leak = 1.5 kg/s

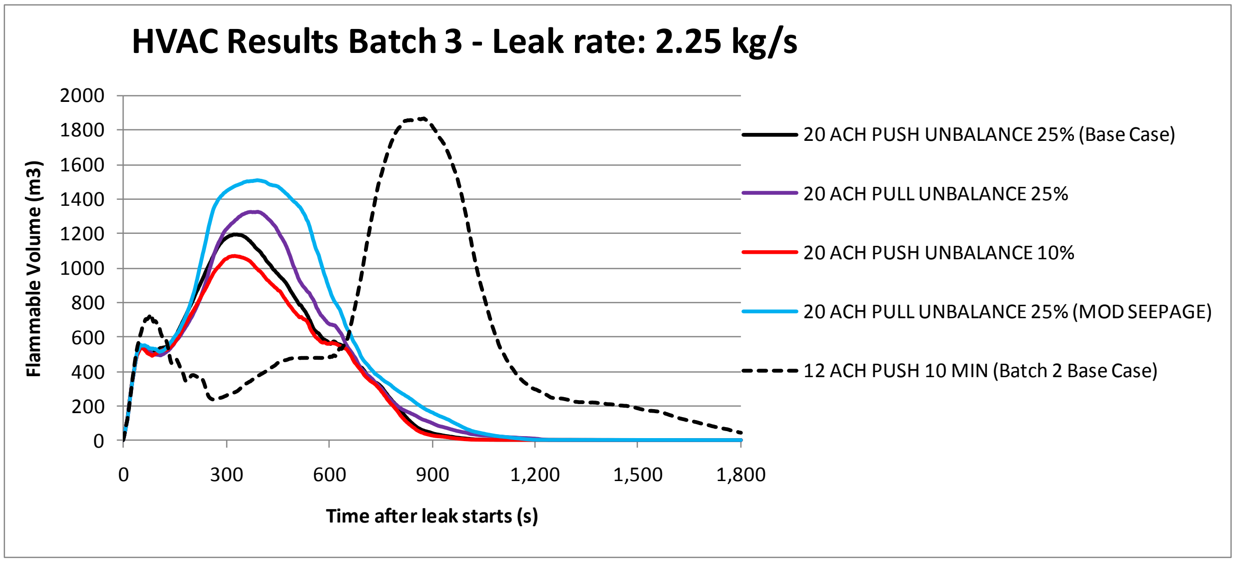

Figure 11: Transient development of flammable gas – initial leak = 2.25 kg/s

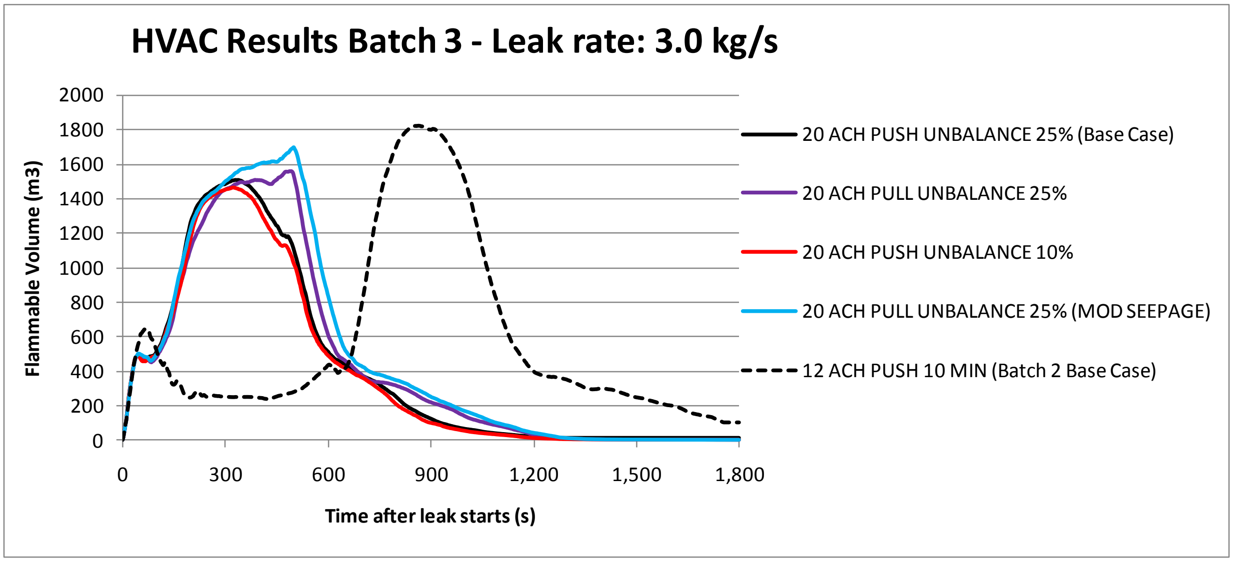

Figure 12: Transient development of flammable gas – initial leak = 3.0 kg/s

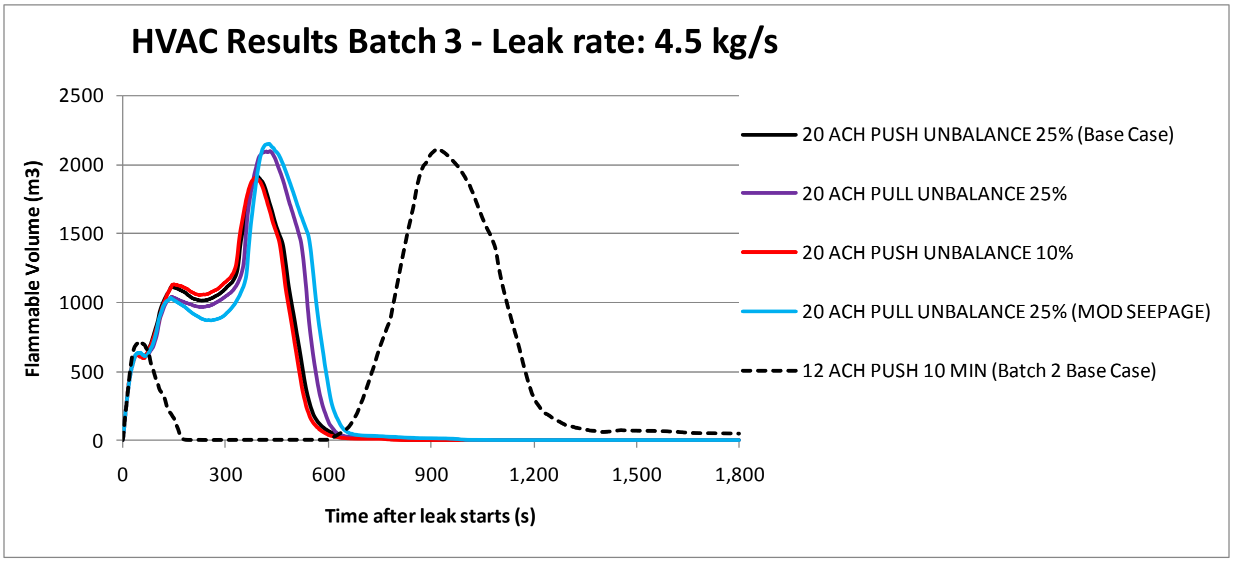

Figure 13: Transient development of flammable gas – initial leak = 4.5 kg/s

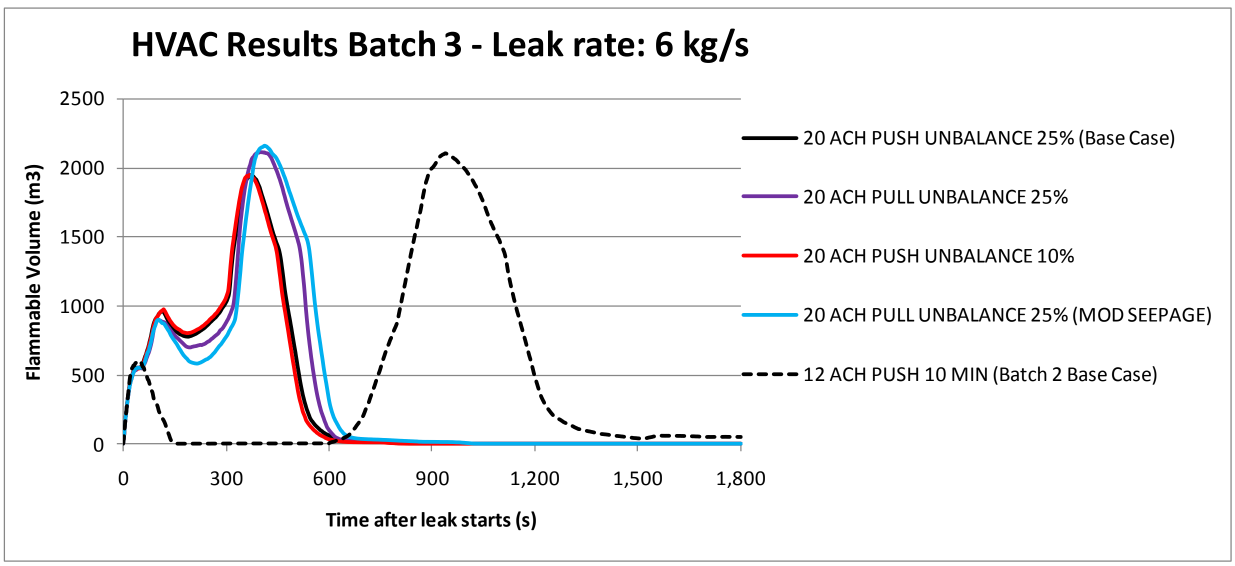

Figure 14: Transient development of flammable gas – initial leak = 6 kg/s

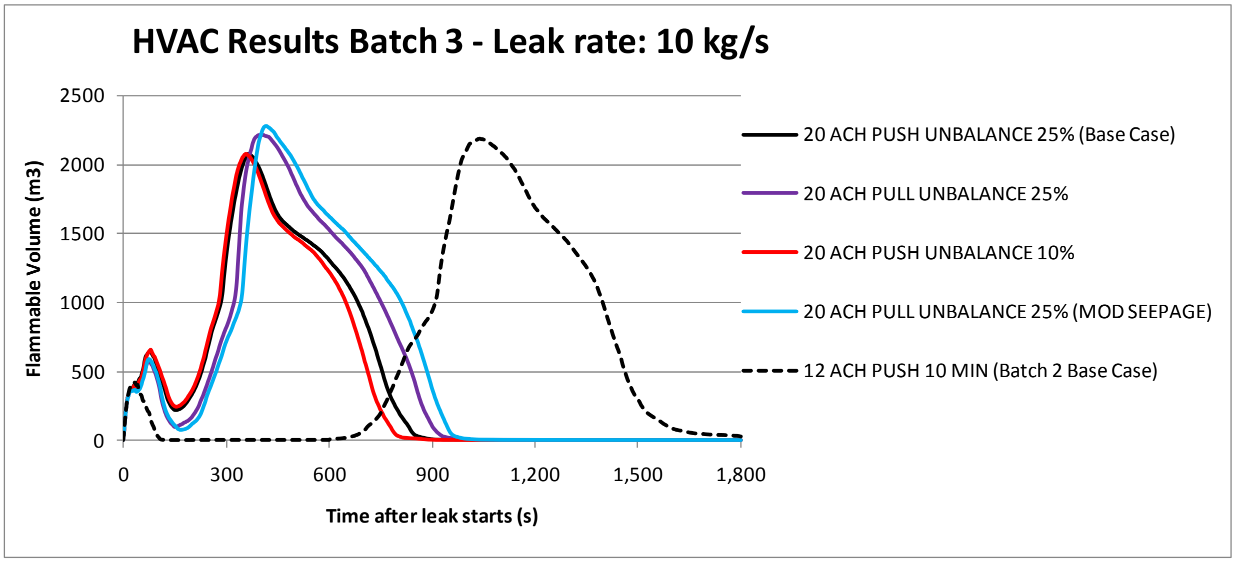

Figure 15: Transient development of flammable gas – initial leak = 10 kg/s

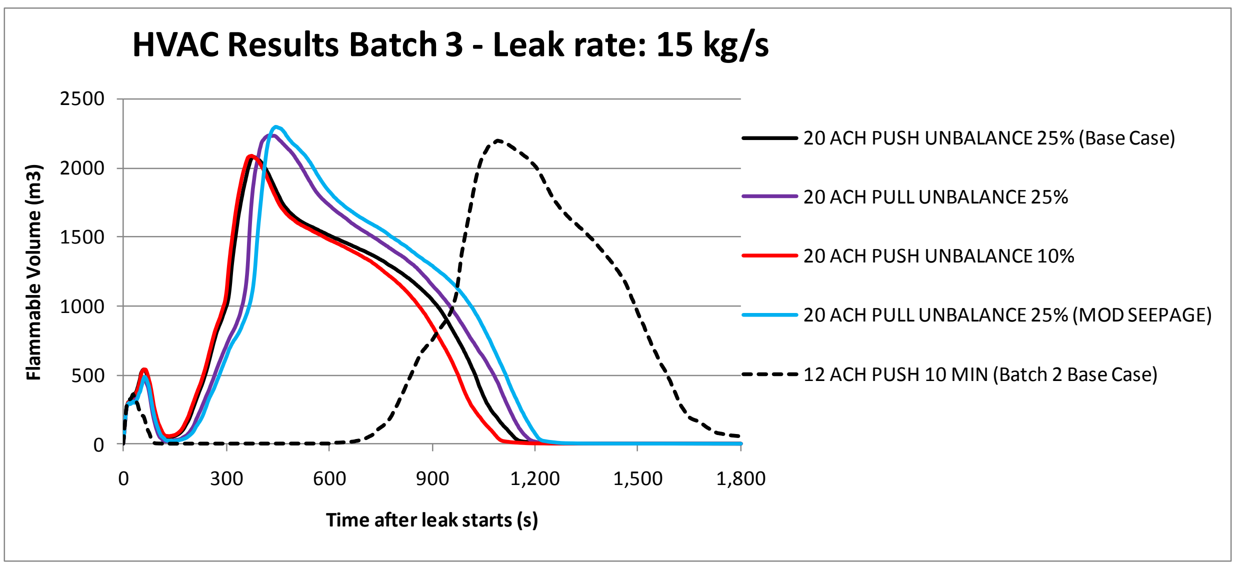

Figure 16: Transient development of flammable gas – initial leak = 15 kg/s

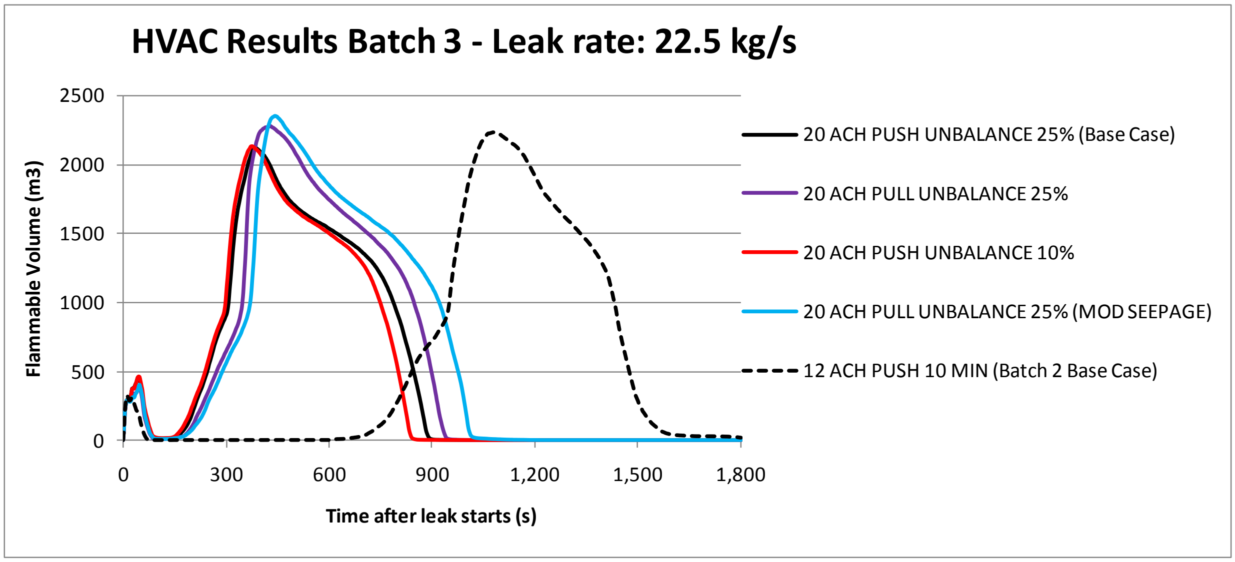

Figure 17: Transient development of flammable gas – initial leak = 22.5 kg/s

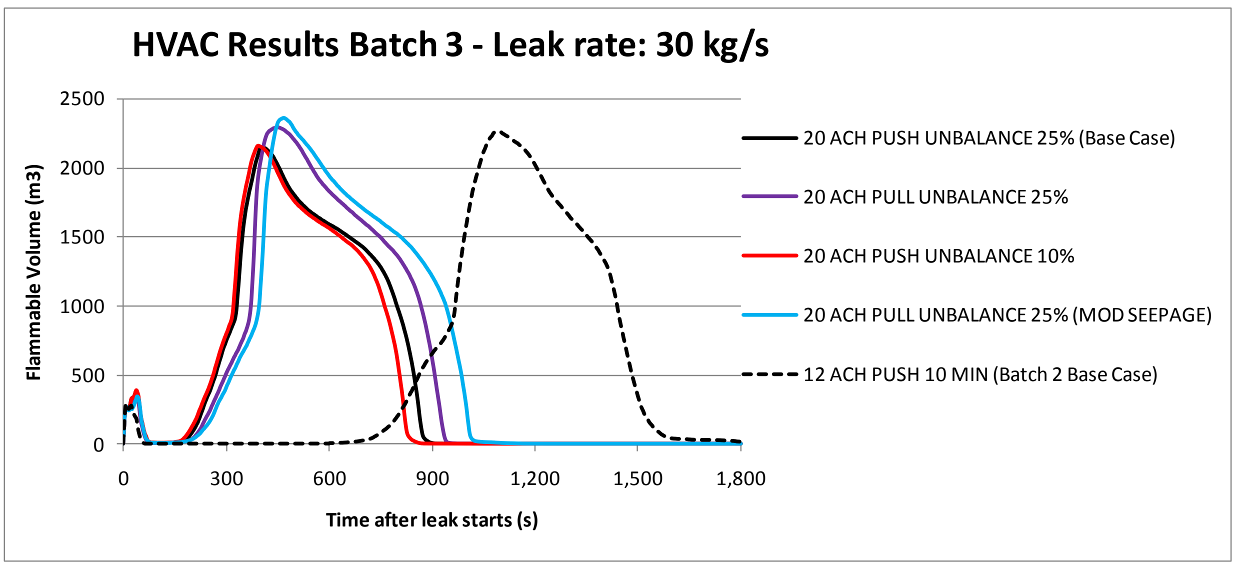

Figure 18: Transient development of flammable gas – initial leak = 30 kg/s

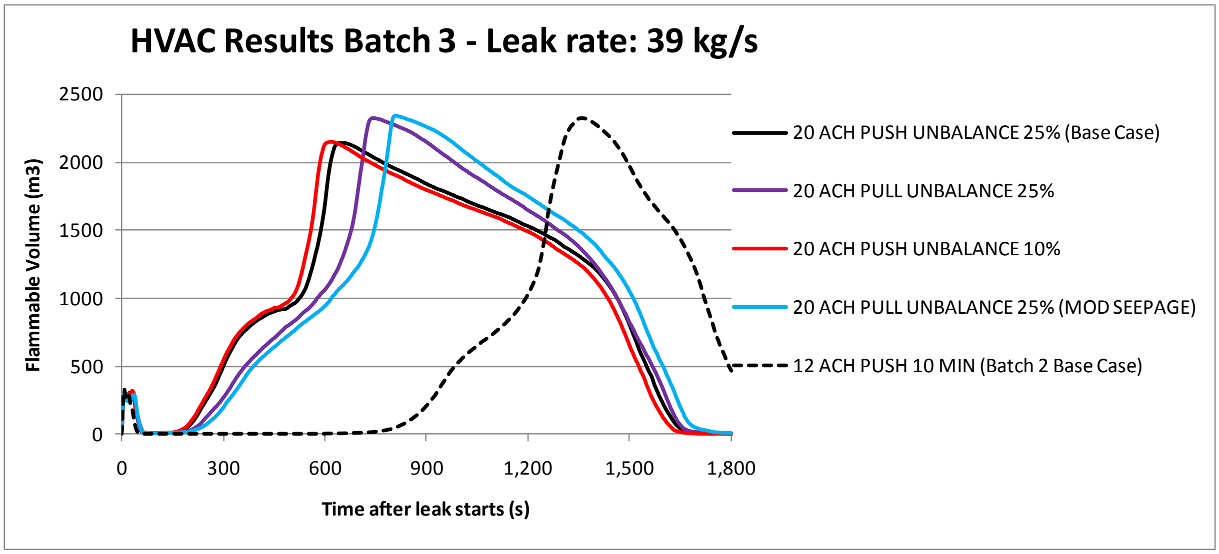

Figure 19: Transient development of flammable gas – initial leak = 39 kg/s

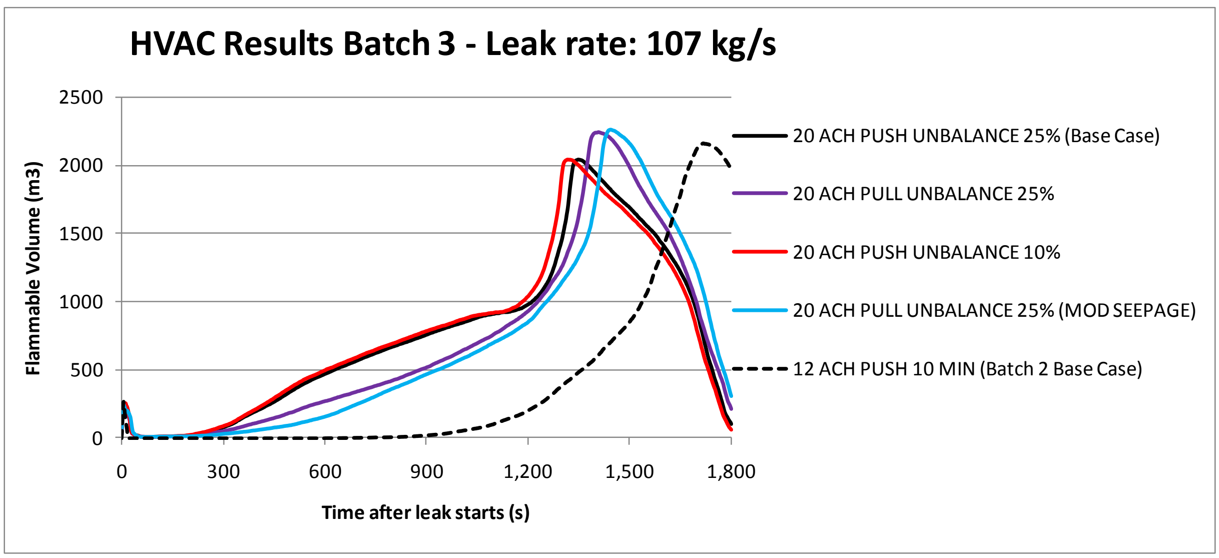

Figure 20: Transient development of flammable gas – initial leak = 107 kg/s

8.6 P05 GAS COMPRESSOR MODULE

The resulting transient flammable volumes from the FLACS simulations for the P05 Gas Compressor Module are presented in Figure 21 through Figure 38. All FLACS scenarios are simulated in 1800 seconds (i.e. gas is traced approximately for 600-1200 seconds after the leak has stopped). The 1800 seconds simulation time is due to the time limit of ExploRAM (simulating only 1800 seconds of contribution from ignition sources).

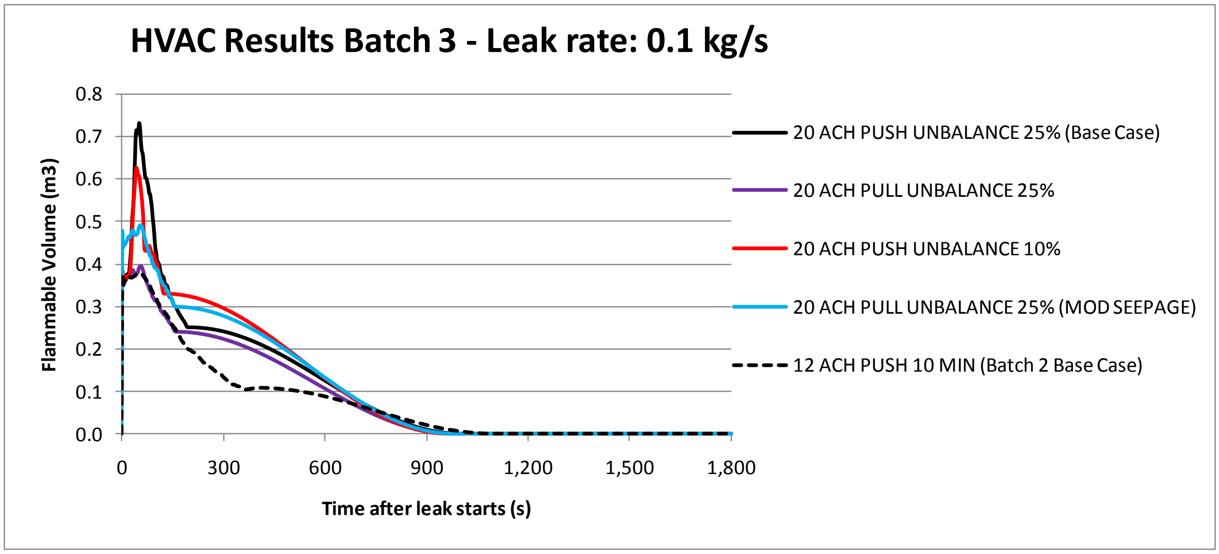

Figure 21: Transient development of flammable gas – initial leak rate = 0.1 kg/s. Note that all calculated volumes are insignificant

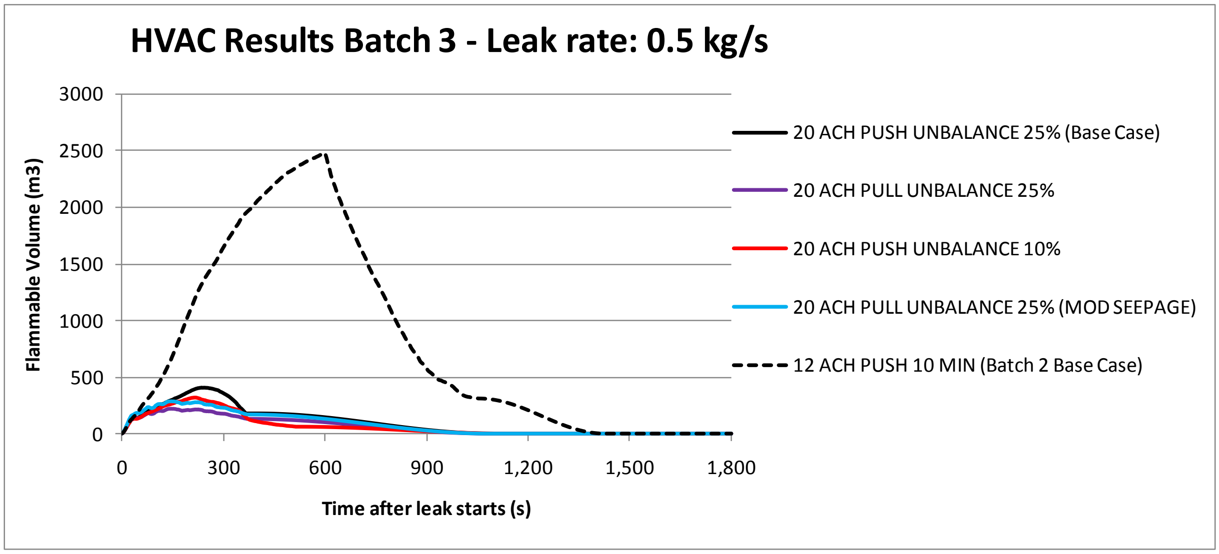

Figure 22: Transient development of flammable gas – initial leak rate = 0.5 kg/s

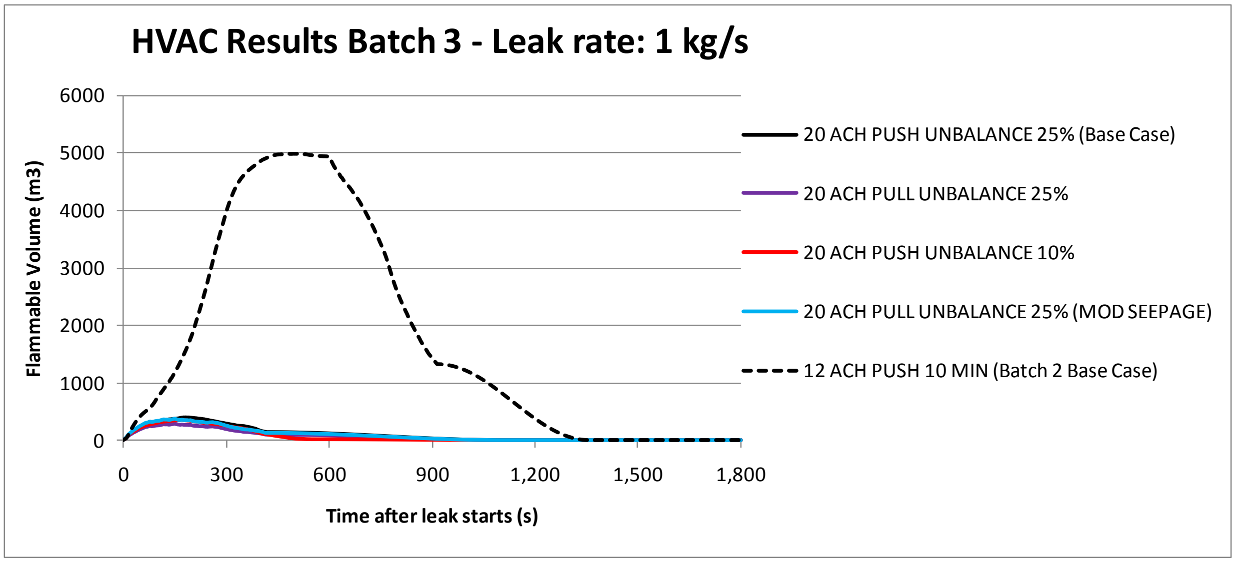

Figure 23: Transient development of flammable gas – initial leak rate = 1 kg/s

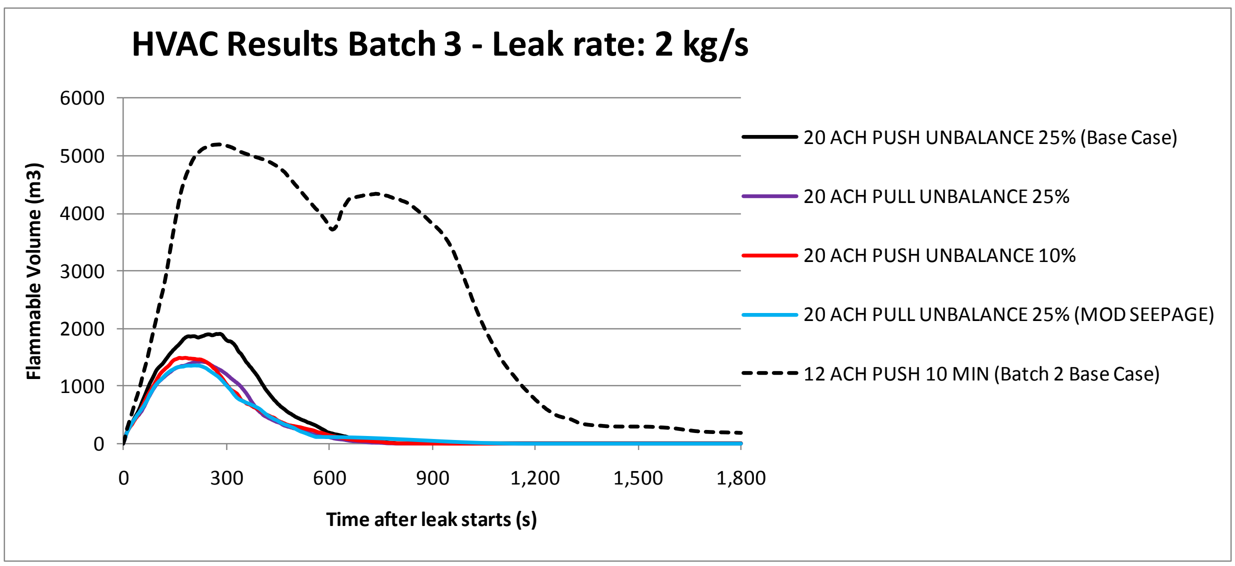

Figure 24: Transient development of flammable gas – initial leak rate = 2 kg/s

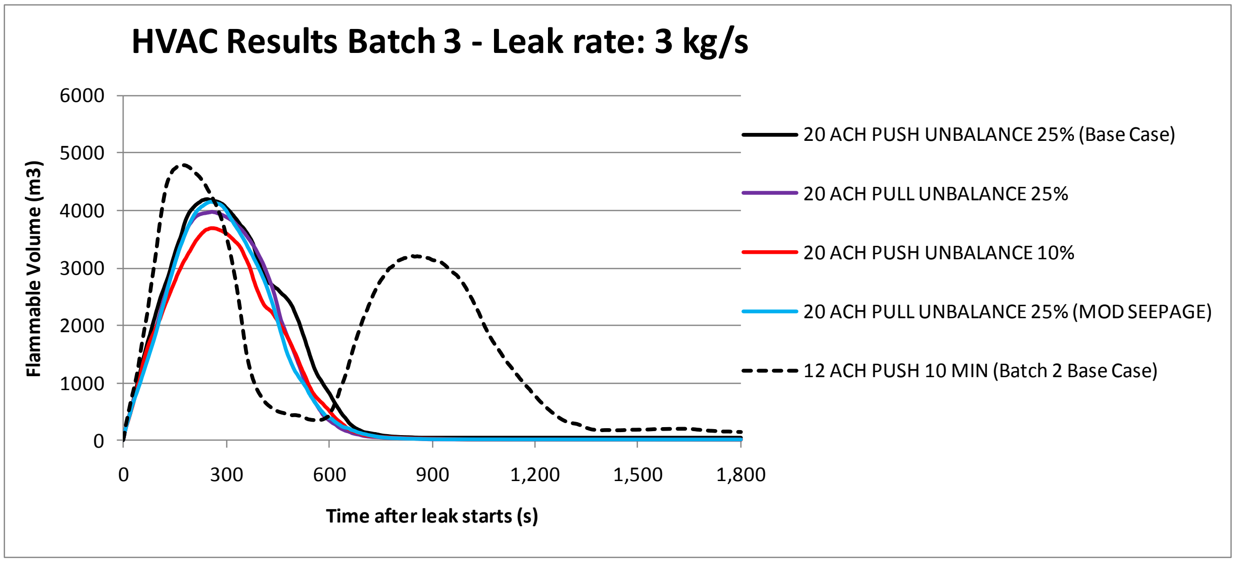

Figure 25: Transient development of flammable gas – initial leak rate = 3 kg/s

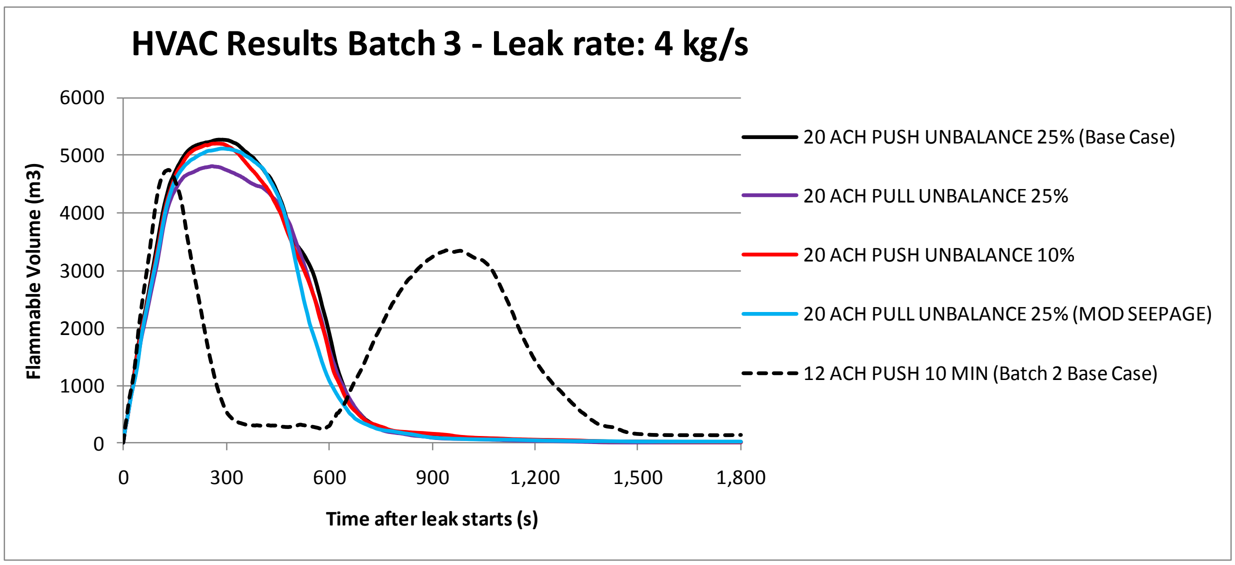

Figure 26: Transient development of flammable gas – initial leak rate = 4 kg/s

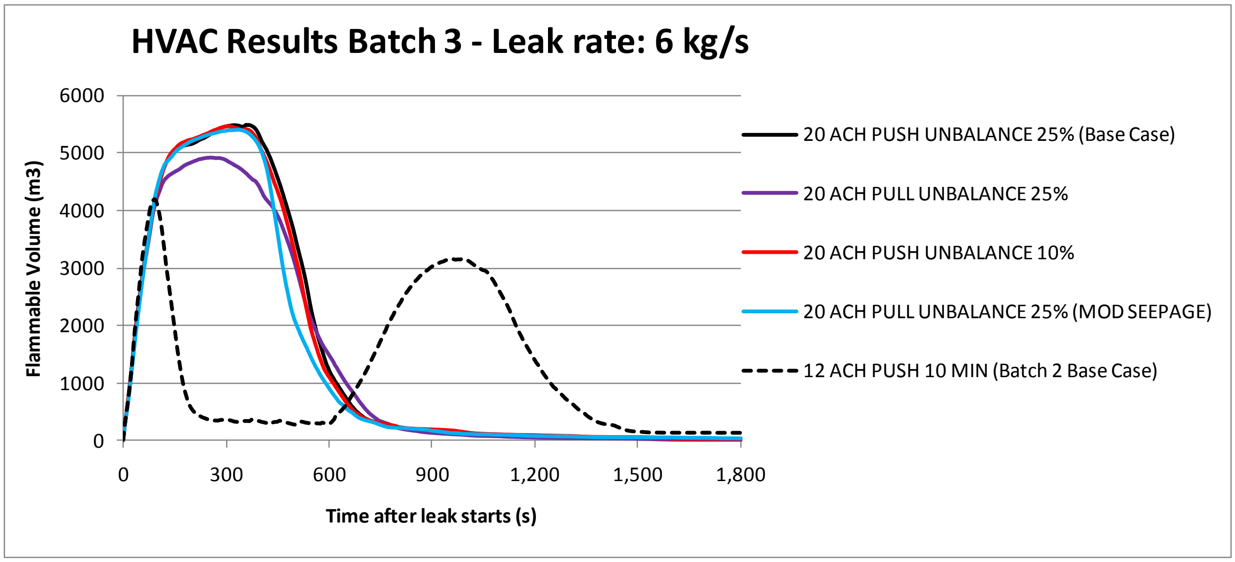

Figure 27: Transient development of flammable gas – initial leak rate = 6 kg/s

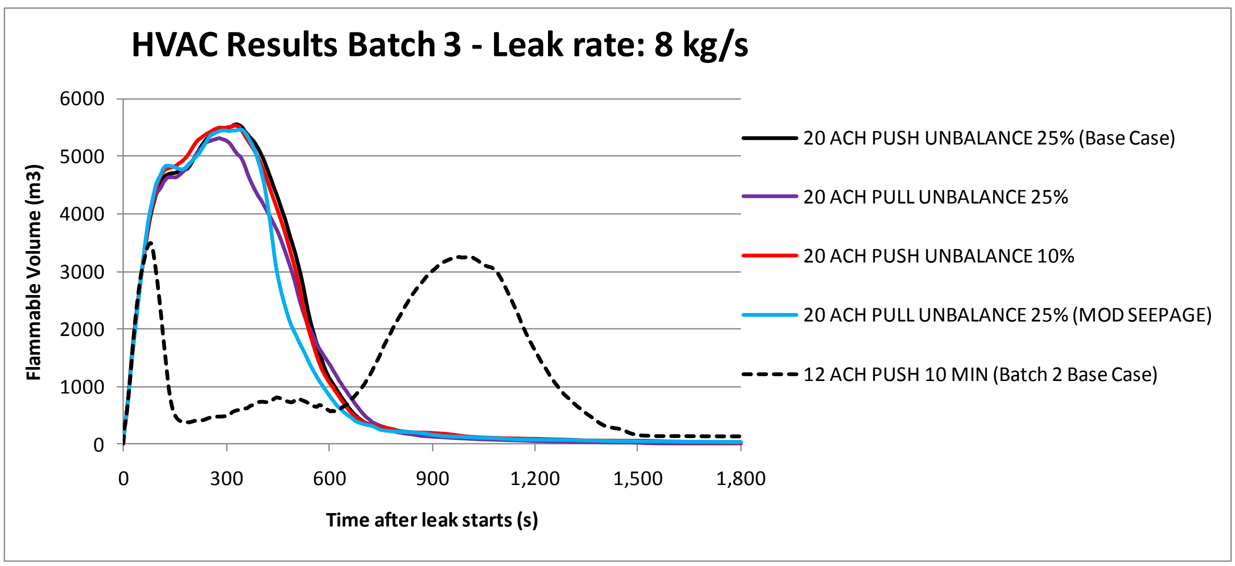

Figure 28: Transient development of flammable gas – initial leak rate = 8 kg/s

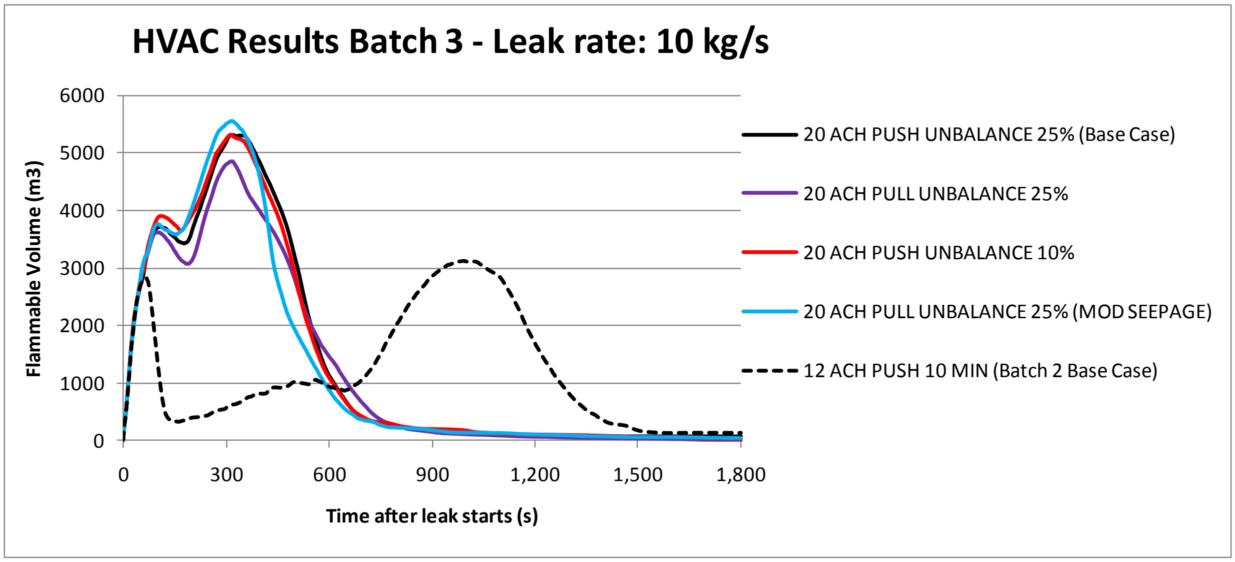

Figure 29: Transient development of flammable gas – initial leak rate = 10 kg/s

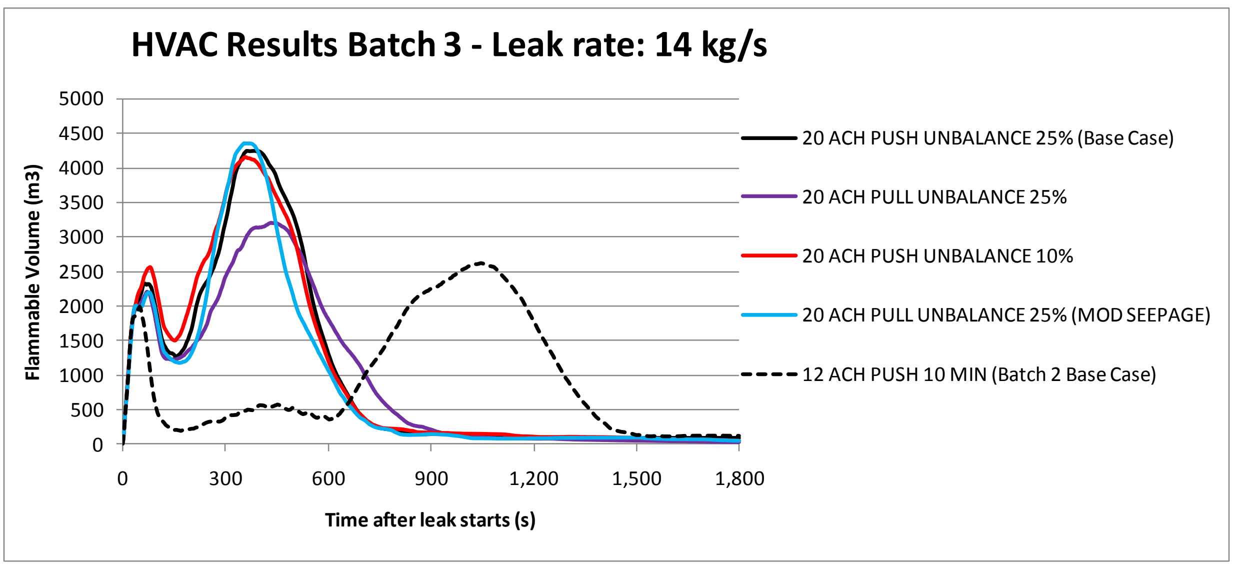

Figure 30: Transient development of flammable gas – initial leak rate = 14 kg/s

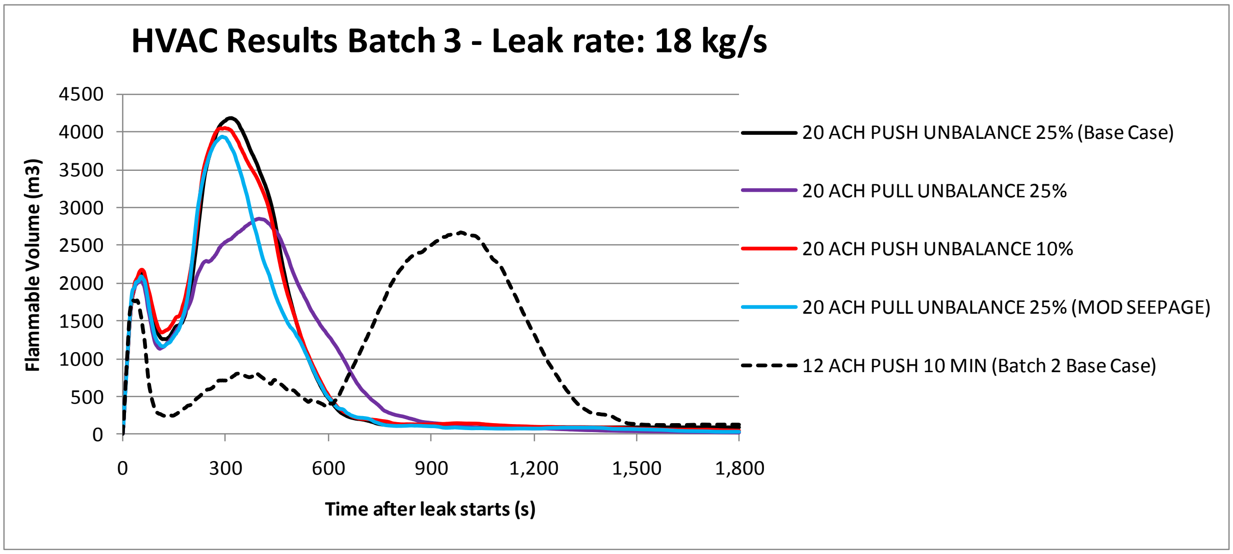

Figure 31: Transient development of flammable gas – initial leak rate = 18 kg/s

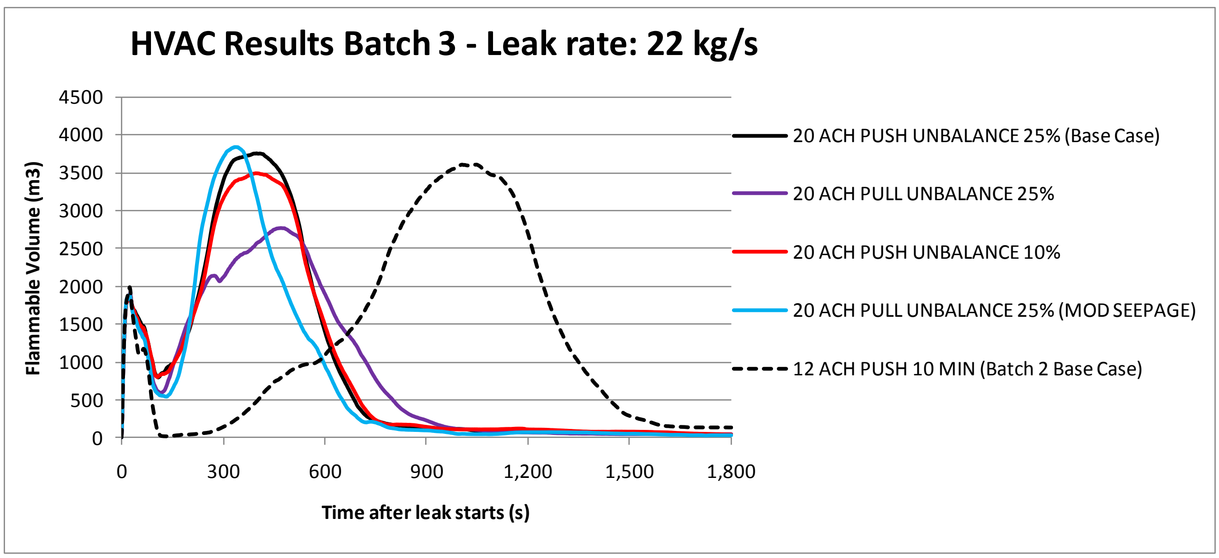

Figure 32: Transient development of flammable gas – initial leak rate = 22 kg/s

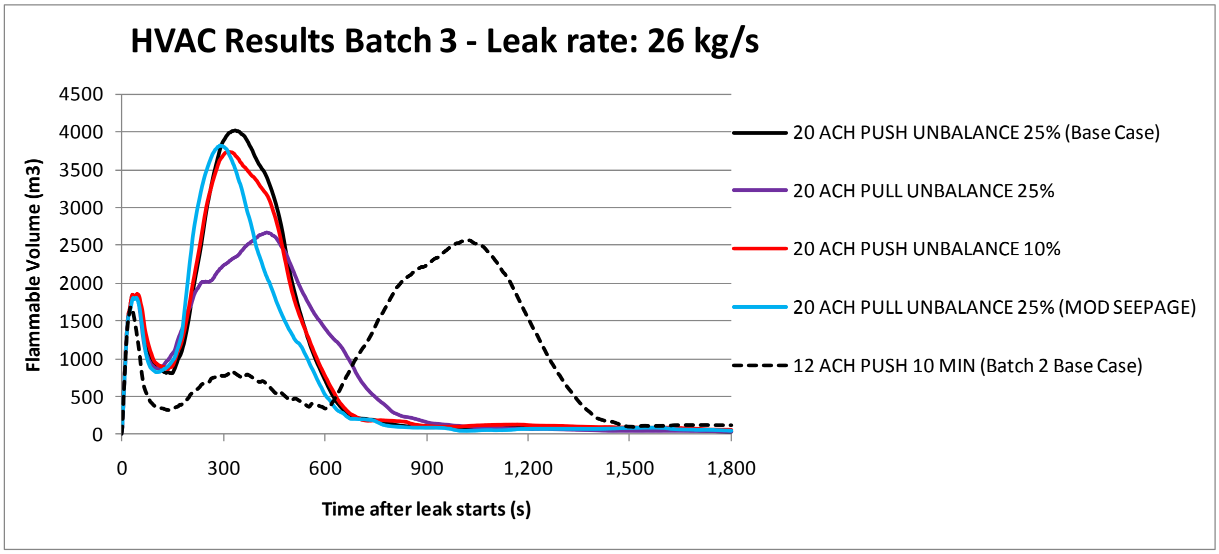

Figure 33: Transient development of flammable gas – initial leak rate = 26 kg/s

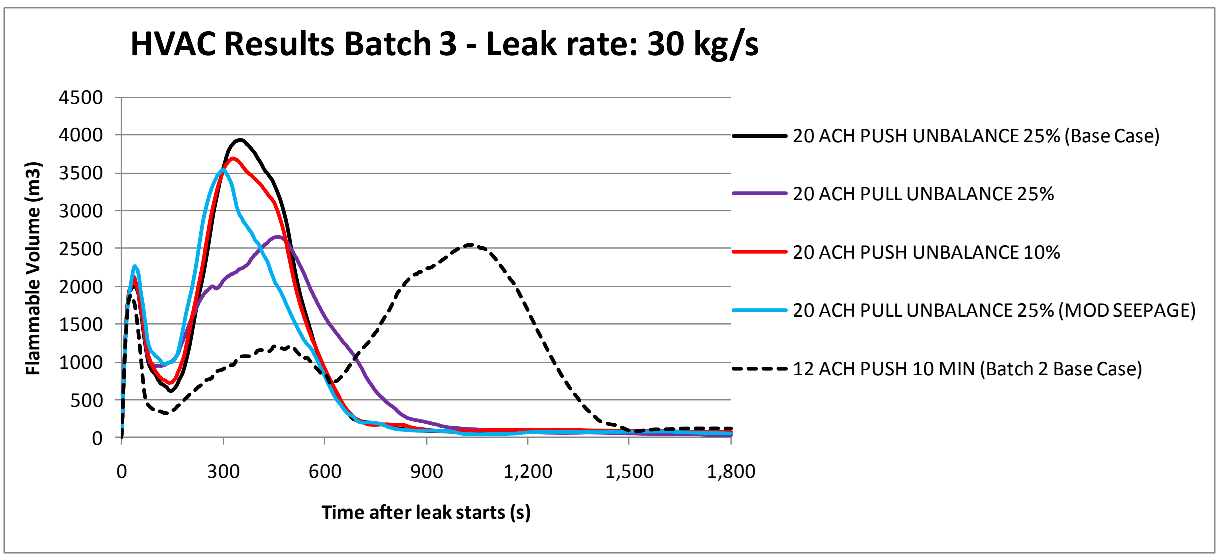

Figure 34: Transient development of flammable gas – initial leak rate = 30 kg/s

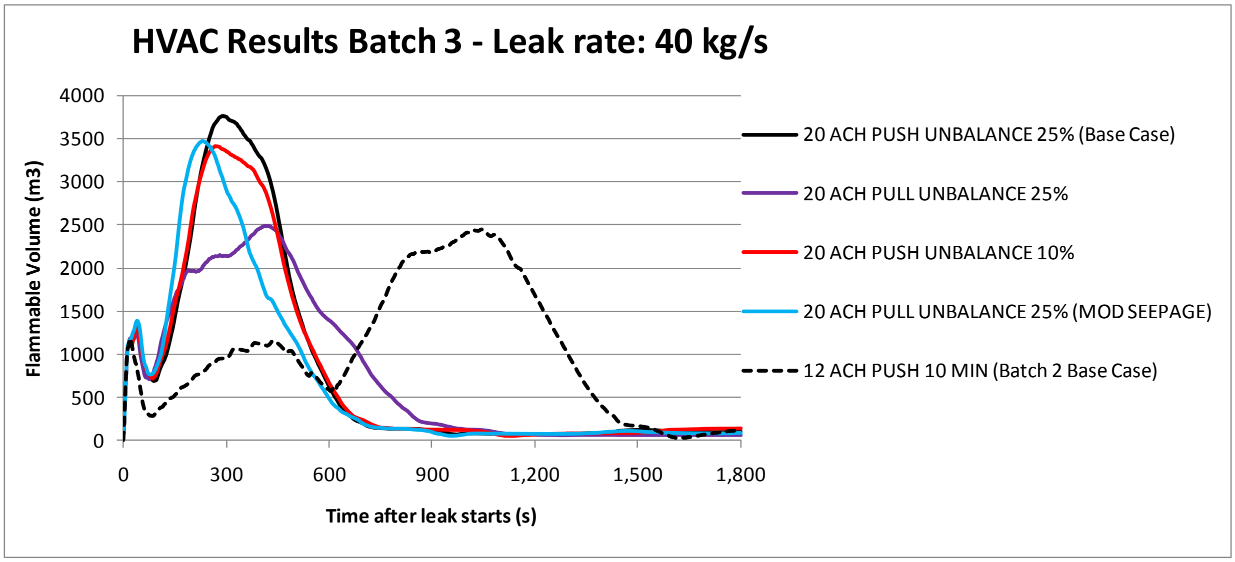

Figure 35: Transient development of flammable gas – initial leak rate = 40 kg/s

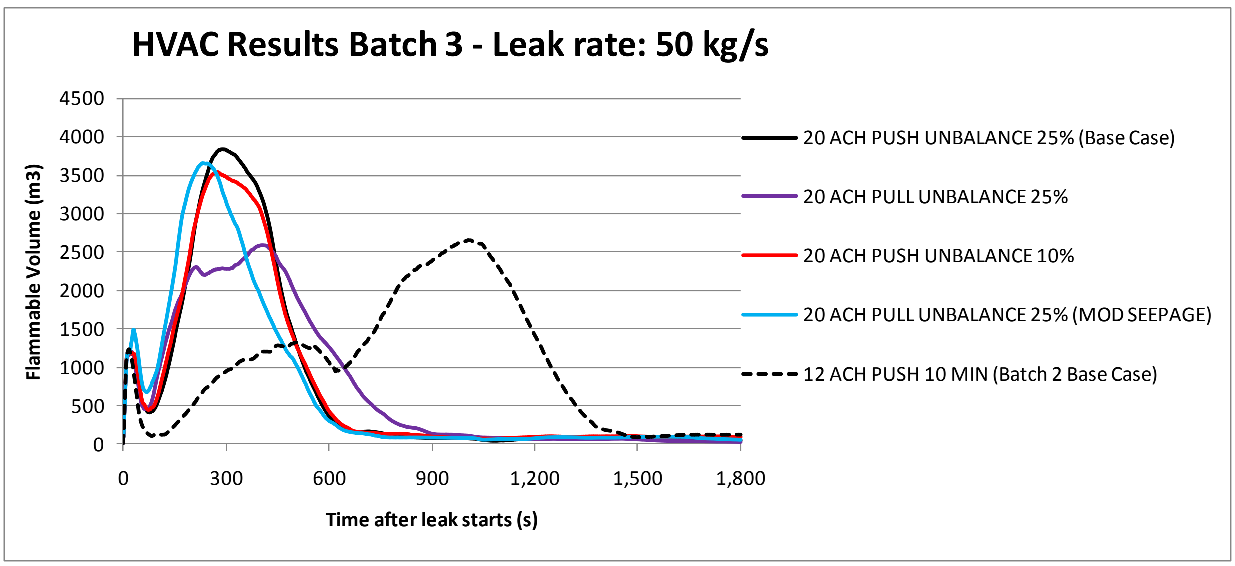

Figure 36: Transient development of flammable gas – initial leak rate = 50 kg/s

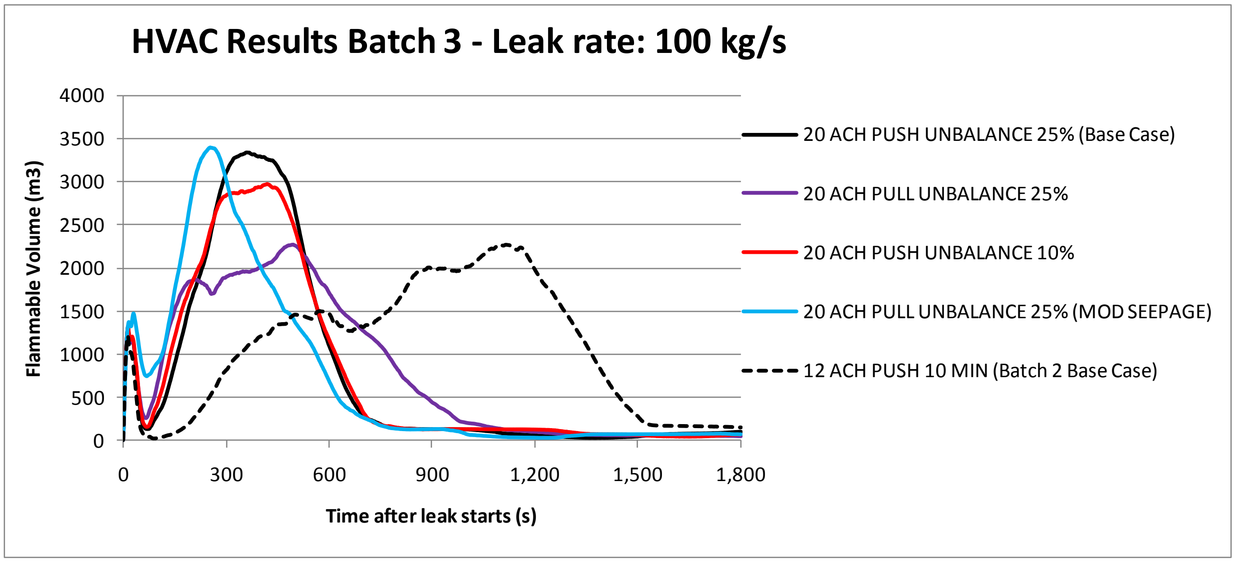

Figure 37: Transient development of flammable gas – initial leak rate = 100 kg/s

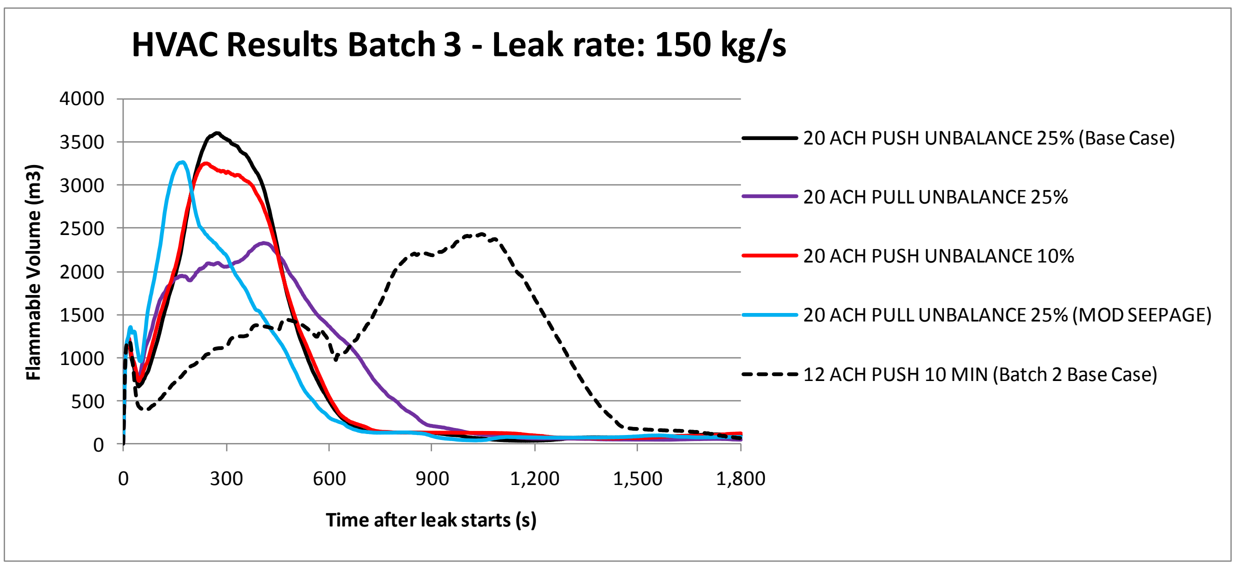

Figure 38: Transient development of flammable gas – initial leak rate = 150 kg/s

8.7 IGNITION MODELING

IGNITION SOURCES

The ignition sources for the P01 Manifold and P05 Compressor Modules are presented in Table 2 and Table 3. For further description of the ignition sources, see Ref. /2/.

Table 2: Ignition sources for the P01 Manifold module

Ignition Source	
Electrical equipment (area, m2)	523
Pump (no. of items)	0.03
Compressor (no. of items)	0
Other (area, m2)	523
Personnel (area, m2)	523
Hot work (hours per year)	50

Table 3: Ignition sources for the P05 Gas Compressor module

Ignition Source	
Electrical equipment (area, m2)	1230
Pump (no. of items)	2
Compressor (no. of items)	0
Other (area, m2)	307.5
Personnel (area, m2)	307.5
Hot work (hours per year)	50

8.8 GAS DETECTORS

In the present study it is assumed 19 and 44 point gas detector equivalents in the P01 Manifold and P05 Gas Compressor modules, respectively (19 point detector equivalents implies that the total number of actual point and line detectors represent in average the same detection efficiency as 19 uniformly distributed point detectors).

It is assumed that confirmed gas is represented by 20% LFL on one detector and 30% LFL on another detector. The actual philosophy has not been modeled directly in the ExploRAM model. This is due to limitations in the current version of ExploRAM, and the actual detection configuration would have had to be converted into a uniformly distributed detector equivalent. From the gas dispersion simulations it has been seen that for medium leaks (which are the dominating explosion risk contributor) the gas will be detected (when 20% LFL volume exceeds approximately 200 m^3) within 4 to 11 seconds. And (almost) any gas detection system will effectively detect the critical gas clouds (the clouds that are potentially large enough to cause a strong explosion). In addition, the difference between the 20% LFL and the 40% LFL is not significant in the first phase of the cloud development (see Figure 2.31 and Figure 2.32) and the actual value to be used in ExploRAM is, therefore, not significant for the conclusions of the study.

8.9 P01 MANIFOLD MODULE

8.9.1 PRESSURE-FREQUENCY CURVE

The probabilistic results are obtained from combining the dispersion results of the previous sections of this study, ignition source data and explosion results from other portions of this series of studies.. The pressure frequency is established from the maximum local loads in the module. Since the platform is expected to be exposed to icing no more than 50% of the year, the explosion loads in Figure 39 are increased by 17% when establishing the final pressure-frequency curves to be used to establish design load. The same icing factor is used in all Phase 3 explosion studies.

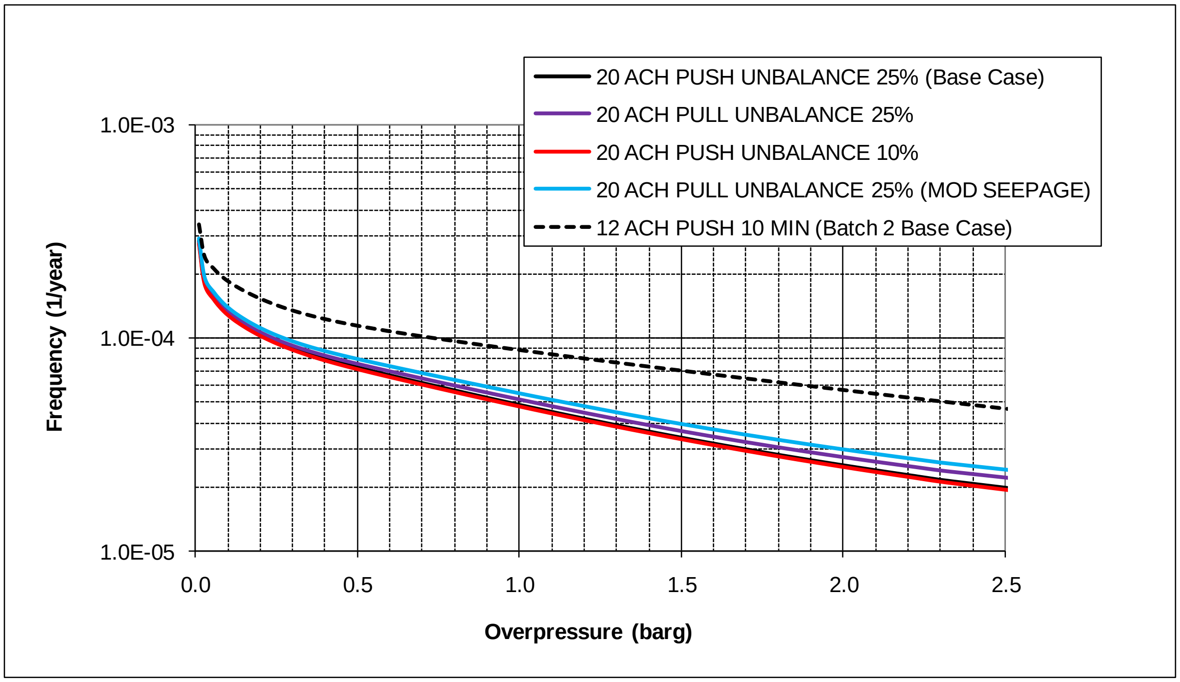

Figure 39: Pressure frequency curves for explosions in the P01 Manifold module

The corresponding 10^{-4}, $8 \cdot 10^{-5}$ and 10^{-5} loads are presented in Table 4, Table 5 and Table 6, respectively.

Table 4: Calculated load with frequency 10-4 for the P01 Manifold module

Configuration	Pressure (1E-4) barg	Diff from Base Case
20 ACH PUSH UNBALANCE 25% (Base Case)	0.22	0.0%
20 ACH PULL UNBALANCE 25%	0.24	7.5%
20 ACH PUSH UNBALANCE 10%	0.21	-4.2%
20 ACH PULL UNBALANCE 25% (MOD SEEPAGE)	0.27	21.6%
12 ACH PUSH 10 MIN (Batch 2 Base Case)	0.74	233.2%

Table 5: Calculated load with frequency 8E-5 for the P01 Manifold module

Configuration	Pressure (8E-5) barg	Diff from Base Case
20 ACH PUSH UNBALANCE 25% (Base Case)	0.40	0.0%
20 ACH PULL UNBALANCE 25%	0.44	10.0%
20 ACH PUSH UNBALANCE 10%	0.38	-4.1%
20 ACH PULL UNBALANCE 25% (MOD SEEPAGE)	0.51	27.6%
12 ACH PUSH 10 MIN (Batch 2 Base Case)	1.21	206.2%

Table 6: Calculated load with frequency 10-5 for the P01 Manifold module

Configuration	Pressure (1E-5) barg	Diff from Base Case
20 ACH PUSH UNBALANCE 25% (Base Case)	4.37	0.0%
20 ACH PULL UNBALANCE 25%	5.19	18.7%
20 ACH PUSH UNBALANCE 10%	4.28	-2.1%
20 ACH PULL UNBALANCE 25% (MOD SEEPAGE)	5.50	25.7%
12 ACH PUSH 10 MIN (Batch 2 Base Case)	6.89	57.5%

8.9.2 FIRE FREQUENCY

The fire frequencies for the different HVAC configurations in the P01 Manifold module are presented in Table 7.

Table 7: Calculated fire frequencies for the P01 Manifold module

Configuration	Fire Frequency	One fire occurs every (years)
20 ACH PUSH UNBALANCE 25% (Base Case)	2.84E-04	3517
20 ACH PULL UNBALANCE 25%	2.82E-04	3551
20 ACH PUSH UNBALANCE 10%	2.77E-04	3611
20 ACH PULL UNBALANCE 25% (MOD SEEPAGE)	2.93E-04	3418
12 ACH PUSH 10 MIN (Batch 2 Base Case)	3.43E-04	2917

8.9.3 P01 MANIFOLD MODULE CONCLUSIONS

The following has been found from the P01 Manifold study:

- The explosion loads in P01 Manifold module has decreased significantly by changing the HVAC philosophy. The $8 \cdot 10^{-5}$ load has been reduced from 1.21 barg (Base Case Phase 2) to 0.4 barg (Base Case Phase 3), a reduction of 67%

- No significant effect is seen by using a pull system instead of a push system in the Manifold module (approximately 10% increase going to pull)

- No significant effect is seen by changing the unbalance (approximately 4% reduction is seen by reducing the unbalance from 25% to 10%)

- A moderate effect is seen by changing the seepage in P01. The loads increased by approximately 28% (from 0.40 to 0.51 barg) when the seepage openings and the total seepage area were reduced 50% in the pull configuration.

8.10 P05 GAS COMPRESSOR MODULE

8.10.1 PRESSURE-FREQUENCY CURVE

The probabilistic results are obtained by combining the dispersion results of the previous sections of this study, ignition source data and explosion results are from another in this series of studies. The pressure frequency is established from the maximum local loads in the module. Since the platform is expected to be exposed to icing no more than 50% of the year, the explosion loads in Figure 40 are increased by 17% when establishing the final pressure-frequency curves to be used to establish design loads.

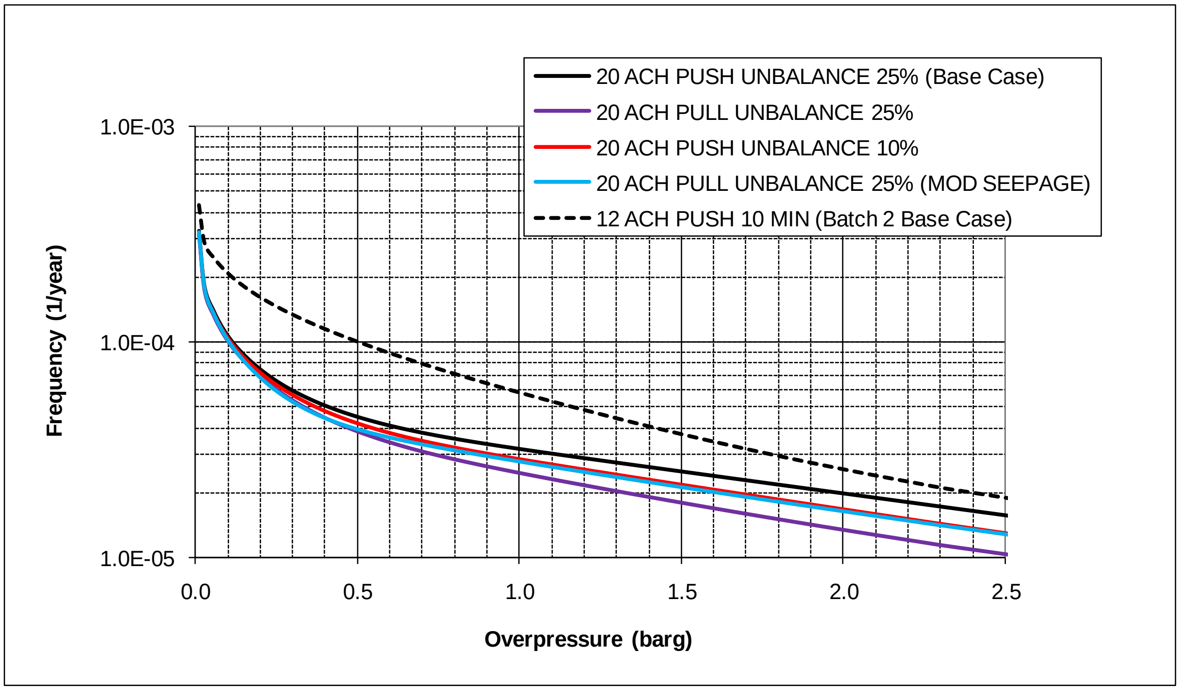

Figure 40: Pressure frequency curves for explosions in the P05 Compressor module

The corresponding 10-4, 8·10-5 and 10-5 loads are presented in Table 8, Table 9 and Table 10, respectively.

Table 8: Calculated load with frequency 10-4 for the P05 Compressor module

Configuration	Pressure (1E-4) barg	Diff from Base Case
20 ACH PUSH UNBALANCE 25% (Base Case)	0.12	0.0%
20 ACH PULL UNBALANCE 25%	0.10	-10.1%
20 ACH PUSH UNBALANCE 10%	0.11	-5.5%
20 ACH PULL UNBALANCE 25% (MOD SEEPAGE)	0.11	-8.6%
12 ACH PUSH 10 MIN (Batch 2 Base Case)	0.50	334.3%

Table 9: Calculated load with frequency $8 \cdot 10^{-5}$ for the P05 Compressor module

Configuration	Pressure (8E-5) barg	Diff from Base Case
20 ACH PUSH UNBALANCE 25% (Base Case)	0.18	0.0%
20 ACH PULL UNBALANCE 25%	0.16	-11.8%
20 ACH PUSH UNBALANCE 10%	0.17	-6.6%
20 ACH PULL UNBALANCE 25% (MOD SEEPAGE)	0.16	-12.1%
12 ACH PUSH 10 MIN (Batch 2 Base Case)	0.69	288.1%

Table 10: Calculated load with frequency 10-5 for the P05 Compressor module

Configuration	Pressure (1E-5) barg	Diff from Base Case
20 ACH PUSH UNBALANCE 25% (Base Case)	3.47	0.0%
20 ACH PULL UNBALANCE 25%	2.58	-25.7%
20 ACH PUSH UNBALANCE 10%	3.02	-13.0%
20 ACH PULL UNBALANCE 25% (MOD SEEPAGE)	3.03	-12.6%
12 ACH PUSH 10 MIN (Batch 2 Base Case)	3.76	8.2%

8.10.2 FIRE FREQUENCY

The fire frequencies for the different configurations in the P05 Compressor module are presented in Table 11.

Table 11: Calculated fire frequencies for the P05 Compressor module

Configuration	Fire Frequency	One fire occurs every (years)
20 ACH PUSH UNBALANCE 25% (Base Case)	3.28E-04	3046
20 ACH PULL UNBALANCE 25%	3.19E-04	3137
20 ACH PUSH UNBALANCE 10%	3.22E-04	3110
20 ACH PULL UNBALANCE 25% (MOD SEEPAGE)	3.23E-04	3092
12 ACH PUSH 10 MIN (Batch 2 Base Case)	4.31E-04	2323

The following has been found from the P05 Gas Compressor study:

The explosion loads in P05 Gas Compression module has decreased significantly by changing the HVAC philosophy. The $8{\cdot}10^{-5}$ load has been reduced from 0.69 barg (Base Case Phase 2) to 0.18 barg (Base Case Phase 3), a reduction of 74%

No significant effect is seen by using a pull system instead of a push system in the Manifold module (approximately 12% increase when going to pull)

No significant effect is seen by changing the unbalance (approximately 7% reduction is seen by reducing the unbalance from 25% to 10%)

A moderate effect is seen by changing the seepage in P05. The loads decreased approximately 12% (from 0.18 to 0.16 barg) when the seepage openings and the total seepage area were reduced 50% in the pull configuration.

Please refer to Section 6.0 for the conclusions drawn from this modeling series.